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ANALYTICAL STUDY OF ARMY DEMOLITION FORMULAE

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An analytical study was performed ~~utilizing~~ experimental test data realized from 8 years of previous demolition programs conducted by USAERDL/USAMERDC, Fort Belvoir, Virginia.

Data which were analyzed related to the demolition of prestressed concrete bridge members, the cutting of steel structural elements, and the cutting of standard timber. The formulae developed from the experimental data are compared to the formulae and relationships contained in FM5-25, *Explosives and Demolition,* February 1971.

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SUMMARY

An analytical study was performed utilizing experimental test data realized in previous demolition programs conducted by USAERDL and USAMERDC, Fort Belvoir, Virginia.

Data which were analyzed related to the demolition of prestressed concrete bridge members, the cutting of steel structural elements, and the cutting of standing timber. The formulae developed from the experimental data are compared to the formulae and relationships contained in the latest FM 5-25, *Explosives and Demolitions.*

Conclusions include:

a. Dual-side-breaching of prestressed concrete beams represents an appreciable savings in explosive requirements, followed by demolition of the beam from the bottom face of the tension flange, with pressure charges on the top face of the compression flange requiring the greatest amount of explosives for demolition.

b. The cutting of steel is much more subjective than is indicated by the general formulae contained in FM 5-25. The experimental data reflect a wide variance in the values for the formulae coefficients which relate explosive weight to the parameters of cross section, diameter, and the square of the diameter.

c. The experimental timber-cutting data reflect fair correlation to the general formulae in FM 5-25.

d. There is a strong correlation of the size of the explosive charge, charge dimension relationships, and the relationship of charge thickness to material thickness for steel cutting.

Suggested future plans include:

a. Development of precomputed tables for operational use to minimize computational error by field personnel.

b. Investigation into the development of nomograms or a demolition slide rule employing graphic symbols which would facilitate use by USA and foreign army personnel.

c. Conduct of further tests for verification and expansion of steel-cutting relationships including evaluation of the following relationship:

$$P = 1.92 \times 10^{-2} \frac{L_E W_E T_M}{k_e}$$

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ANALYTICAL STUDY OF ARMY DEMOLITION FORMULAE

I. INTRODUCTION

1. **General.** This analytical study of Army demolition formulae is submitted by the Systems Engineering Division to the Barrier Division, USAMERDC, in response to the Disposition Form, reference SMEFB-MW, 5 October 1972, from Roger Lum, Project Engineer, Barrier Division.

2. **Study Objectives.** The objectives established for the study are:

a. Revise or formulate a new formula for demolition of prestressed bridge members using data obtained in previous USAMERDC experimentations.

b. Revise or formulate a new steel-cutting formula using data obtained in previous USAMERDC experimentations.

c. Investigate tree-cutting data for feasibility of formula revision.

II. SCOPE OF STUDY

3. **General.** This study is a review and analysis of data obtained in prior test programs and an analysis of demolition requirements and formulae from FM 5-25.[1] The test data covered a period of about 8 years. The data are evaluated for standard explosives using existing formulae and parameters available in FM 5-25. The evaluations form the bases for the conclusions and suggested future plans derived for this study.

4. **Explosive Calculation Formulae.** Table 1 shows the standard formulae which are currently employed and available in FM 5-25 for calculating the demolition charge requirements. These formulae and parameters are basic to this study and provide an initial baseline for the evaluation of the referenced experimental data. Table 2 shows these formulae when all the dimensions are in inches. They were calculated to facilitate the analyses of test data.

5. **Reference Data.** Table 3 shows the experimental data available for explosives and demolition targets for the studies referenced herein and cited in the bibliography. Only the data relating to the standard military explosives are considered for this analytical study.

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[1] FM 5-25, *Explosives and Demolitions*, Headquarters, Department of the Army, February 1971.

Table 1. Explosive Calculation Formulae (Source FM 5-25)

Pressure Charges	Breaching Charges	Timber-Cutting Charges	Steel-Cutting Charges
$P=4H^2T$ (untamped) $P=3H^2T$ (tamped)	$P=R^3KC$ Number of charges $N=W/2R$	$P=D^2/40$ (external) $P=D^2/250$ (internal, tamped)	Structural members $P=3/8A$ Other steel members $P=D^2$ Steel bars of $D \leq 2''$ $P=D$

Legend:

- P=pounds of TNT required*
- H=height of stringer, including roadway
- T=thickness of stringer in feet
- R=breaching radius in feet (rounded off to next higher ½ foot)
- K=material factor from Table XI, FM 5-25
- C=tamping factor (Fig. 105, FM 5-25)
- N=number of charges required
- W=width of pier, slab, or wall in feet
- R=breaching radius in feet
- D=diameter of section to be cut (inches)
- A=cross-sectional area to be cut in square inches

Note:

When the value for N has a fraction less than ½, the fraction is disregarded. When the fraction is ½ or more, the value is rounded off to the next higher whole number. For values between 1 and 2, round off to 2 when the fraction is ¼ or greater.

Railroad Rails: ½ pound of explosive for height of 5" or less (80# rail): 1 pound of explosive for height over 5".

Saddle Charge:
base of charge = ½ target circumference
long axis of charge = target circumference
thickness of charge = 1" (thickness of M112 block of plastic explosive)

Targets over 25" in circumference require the diamond charge.

Diamond Charge:
long axis of charge = target circumference
short axis = ½ target circumference
thickness of charge = 1"

Ribbon Charge:
thickness of charge = ½ target thickness
width of charge = 3 times charge thickness
length of charge = length of cut

*For explosives other than TNT, use relative-effectiveness factors in FM 5-25.

Table 2. Explosive Calculation Formulae
(Dimensions in inches; charge in pounds)

Explosive	Type of Charge			
	Pressure	Breaching	Timber-Cutting	Steel-Cutting
TNT	Tamped $P=0.00174H^2T$ Untamped $P=0.00232H^2T$	$P=0.000579R^3KC$	External, untamped $P=0.025D^2$ Internal, tamped $P=0.004D^2$	Structural members $P=0.375A$ Other steel members $P=D^2$ Steel bars of $D\leq 2''$ $P=D$
Comp. C-4	Tamped $P=0.00130H^2T$ Untamped $P=0.00173H^2T$	$P=0.000432R^3KC$	External, untamped $P=0.0187D^2$ Internal, tamped $P=0.00299D^2$	Structural members $P=0.280A$ Other steel members $P=0.746D^2$ Steel bars of $D\leq 2''$ $P=0.746D$
Detasheet-C	Tamped $P=0.00152H^2T$ Untamped $P=0.00203H^2T$	$P=0.000508R^3KC$	External, untamped $P=0.0219D^2$ Internal, tamped $P=0.00351D^2$	Structural members $P=0.329A$ Other steel members $P=0.877D^2$ Steel bars of $D\leq 2''$ $P=0.877D$

Table 3. Explosive/Target Reference Data

TARGET / EXPLOSIVE	Mass Concrete	Steel Cutting	Timber Cutting	Prestressed Concrete Member (AASHO Beam Type)			
				Type I Bridge	Type II Bridge	Type III Bridge	Standard Box
C-4	(a) (b)	(c) (d)	(c)	(e)	(f)	(c) (g)	(h)
TNT			(c)			(c) (g)	
EL 506A-5		(d)					
Detasheet C (M118)	(c)	(c)	(c)			(c) (g)	
Non-Standard Sheet							(h)
Paste		(d)					
Aluminized Paste		(d)					
M2A3, 15-lb Shaped Charge					(f)		(h)
M3, 40-lb Shaped Charge					(f)		(h)
DM 19, Linear Shaped Charge				(e)			
DM 29, Linear Shaped Charge				(e)			

(a) Howard J. Vandersluis, *Hasty Demolition of Concrete Structures*, Technical Report 1663-TR, USAERDL, Fort Belvoir, Virginia, January 1961.

(b) Howard J. Vandersluis, *Demolition of Concrete Locks on the Ohio River (Research Phase)*, Technical Report 1730-TR, USAERDL, Fort Belvoir, Virginia, November 1962.

(c) James A. Dennis, *Comparison of Composition C-4 Explosive and M118 Demolition Charges (Detasheet C Explosive) for Military Demolitions*, Report 1900, USAERDL, Fort Belvoir, Virginia, June 1967.

(d) James A. Dennis, *Steel Cutting with High Explosive Charges*, Report 1839, USAERDL, Fort Belvoir, Virginia, December 1965.

(e) James A. Dennis, *Demolition of Prestressed Concrete Bridge Beams with Explosive (Phase I)*, Report 1830, USAERDL, Fort Belvoir, Virginia, September 1965.

(f) James A. Dennis, *Demolition of Post-Tensioned, Prestressed, Concrete Bridge Beams with High-Explosive Charges (Phase IV—Final Phase)*, Report 1959, USAMERDC, Fort Belvoir, Virginia, July 1969.

(g) James A. Dennis, *Demolition of AASHO Standard Type III Prestressed Concrete Beams with High-Explosive Charges (Phase II)*, Report 1853, USAERDL, Fort Belvoir, Virginia, April 1966.

(h) James A. Dennis, *Demolition of Prestressed Concrete Box Beams with High-Explosive Charges (Phase III)*, Report 1897, USAERDL, Fort Belvoir, Virginia, April 1967.

6. **Analytical Study Considerations.** Figure 1 shows the demolition requirements and constraints which apply to any analyses performed for demolition studies. The major elements affecting the charge requirements are the explosive, target, objectives, and environment.

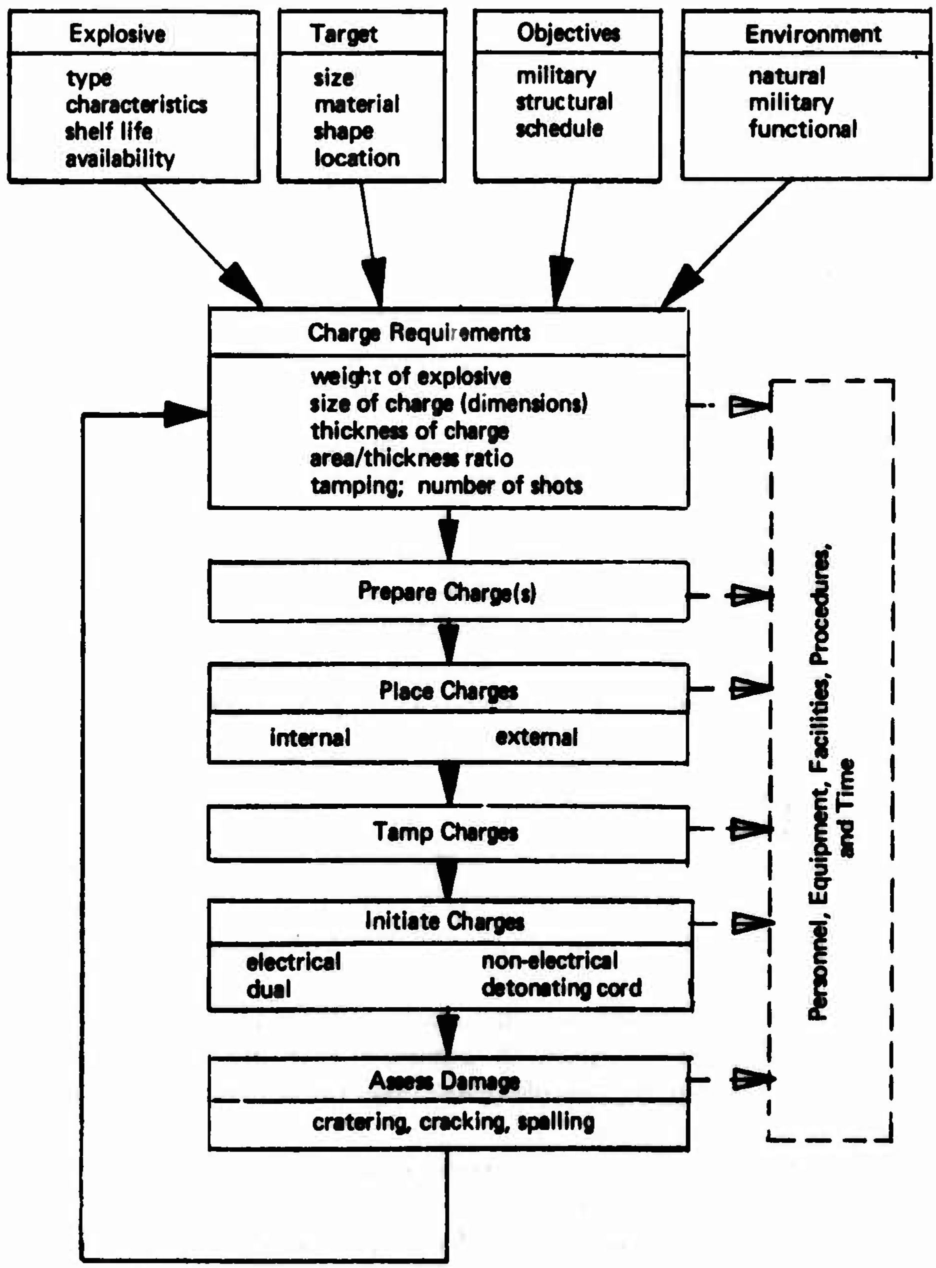

Fig. 1. Demolition requirements/constraints.

Of primary consideration for the charge requirements are the following:

- Weight or amount of explosive
- Size of charge (dimensions, length, width, area, shape)
- Thickness of charge
- Area/thickness ratio of charge
- Tamping
- Number of individual charges (shots)

Primary operational considerations for mission success (function of military objectives) are the penalty of time, which is required, and the resources of material, personnel, and facilities committed to the mission; plus the ability to place the explosive charge at the most critical area of the structure.

The formulae which are derived for demolition use must be applied in the military operational environment by personnel utilizing techniques within the existing training capability of military personnel and within the time constraints established for demolition operations. Operational requirements and applications should be the primary criteria for any demolition research program.

7. **Probable Deviations in Formulae/Experimental Data.** It is not the intent of this study to establish a system error distribution, but the following is introduced to show how some functions and parameters could affect the derivation of formulae. From Fig. 1, it is possible to establish a linear system of operations which in turn affects the variance in the amount of explosive required. Only gross operations/parameters are shown in the following simple relationship:

$$\Delta P = \sqrt{(\Delta M)^2 + (\Delta E)^2 + (\Delta D)^2 + (\Delta J)^2 + (\Delta Z)^2 + (\Delta S)^2}$$

Where:

ΔP = the variation in the amount of the explosive used.

ΔM = the variation in the amount of explosive required as introduced into the formulae based upon the deviation in measurements of the target.

ΔE = the variation in demolition energy output for any given amount of the explosive.

ΔD = the variation caused by the placement, tamping, fastening, etc in the operational environment by operational personnel.

ΔJ = the variation caused by method of initiation and the location of the initiators of the charge.

ΔZ = the variation caused by the method of propagation of the shock-wave energy.

ΔS = the variations caused by the response or reactance of the target structure to the explosive (type, amount).

The relationship is based upon equal probabilities of variance occurring in all the elements shown (each of the element variance is derived for the 50%, 68%, one sigma, two sigma, etc case).

Each of the major elements may be composed of subelements which may be important to each target calculation. When the deviation in the amount of explosive required becomes the most significant factor for operational considerations, then the general formulae must reflect the subjectiveness of the critical, major elements to the degree of control which can be applied in the operational environment.

If each of the six elements shown in the equation above had an equal probability of variance with a value of ± 10% for each, the most probable variance for the explosive requirements would be ± 24%. It should also be pointed out that if one of the six elements has a variance much greater than the others, its effect will obscure the effects of the other five, and any resources expended in experimental determination of the effects of the latter five would be wasted, e.g.

When:

$\Delta M = \pm 10\%$

$\Delta E = \pm 6\%$

$\Delta D = \pm 15\%$

$\Delta J = \pm 15\%$

$\Delta Z = \pm 90\%$

$\Delta S = \pm 30\%$

$$\Delta P = \sqrt{(10)^2 + (6)^2 + (15)^2 + (15)^2 + (90)^2 + (30)^2}$$

$$\Delta P = \sqrt{9586}$$

$$\Delta P = \pm 98\%$$

The negative sign is of significance only to a mathematician; only the +98% variance should have significance for operational formulae. It signifies that if major element effects can vary in the amounts shown, then the probability exists that to insure effective demolition there would be applications which would require approximately twice as much explosive as indicated in the general formulae used for calculating charge requirements.

If in the example it is not possible to determine the unique case which requires the 98% overcharge and operational conditions preclude subsequent demolition

charges, then the general formulae must reflect and be adjusted for the +98% overcharge. Further, if economy of explosive is critical and subsequent demolition charges are permitted, then the general formulae should reflect the average charge requirements instead of accounting for the unique case which requires the +98% overcharge.

8. **Study Approach.** The sequence of operations adopted for this study is as follows:

– Determine the applicable formulae and requirements from the latest revision of FM 5-25.

– Establish the mathematical tables for the parameters employed in the formulae for the standard explosives used in the tests.

– Reference and perform analyses as applicable to define or determine the effects of the operations or parameter variations which could affect the charge calculations.

– Perform charge calculations for specific targets used in the experimental programs.

– Review test data to determine the most probable values for experimental data for comparison to the values calculated above.

– Perform simple statistical operations to determine mean experimental constants and the variance about the mean for each explosive and the applicable formulae.

– Establish new mathematical relationships based upon the new constants derived above.

9. **Supporting Data.** The main body of this study contains the results of the analyses. Supporting, basic data and analytical detail are contained in the following appendices:

A – Demolitions/Explosives
B – Prestressed Concrete Beam Data
C – Steel Data
D – Timber Data
E – Mathematical Tables

The appendices are referenced as applicable in the appropriate sections of this study. The charge calculations and the analytical data in the appendices were accomplished prior to evaluation of the test data of the referenced test programs.

III. DEMOLITION OF PRESTRESSED CONCRETE BEAMS

10. **General.** The use of prestressed concrete structural members has increased significantly since the end of WW II. Essentially, it is a method of construction which utilizes the high-strength (tensile strength of steel, compression strength of concrete) characteristics of steel strands and concrete by introducing stresses into the concrete member during construction (prestressing) which are opposite to those which occur from the dead load of the structure and the live load to be applied. The objective of prestressing is to insure that the concrete in the member will not sustain tensile forces at working loads.

11. **Demolition Objectives.** The primary objective for demolition of prestressed members should be the removal of the prestressing forces in the member. A secondary, or concurrent, objective would be the elimination of the compression capability of the concrete. Both objectives should be accomplished at the most critical (structural loading) area or point of the member. These objectives would be realized with the removal of concrete from the steel strands at the critical section of the member. The forces to be overcome would include the compressive strength and the steel-concrete bond strength of the concrete in the member.

An additional demolition objective would be to cause structural failure by overload at the critical section of the prestressed member. This should be noted from the basic flexural formula used for the design and investigation of structural members subjected to bending forces. The basic flexural formula is contained in Appendix B.

12. **Test Data Validity.** The experimental data realized from Dennis[2-6] were not obtained from prestressed beams which were integral, structural elements of a bridge in an operational configuration. It must be pointed out that the structural response of a single element to a given explosive charge should not be the same as if the element were integral to the total structure. Figures B-1 through B-9, Appendix B, show the element and structures. Other factors which must be considered are:

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[2] James A. Dennis, *Demolition of Prestressed Concrete Bridge Beams with Explosive (Phase I)*, Report 1830, USAERDL, Fort Belvoir, Virginia, September 1965.

[3] James A. Dennis, *Demolition of AASHO Standard Type III Prestressed Concrete Beams with High-Explosive Charges (Phase II)*, Report 1853, USAERDL, Fort Belvoir, Virginia, April 1966.

[4] James A. Dennis, *Demolition of Prestressed Concrete Box Beams with High-Explosive Charges (Phase III)*, Report 1897, USAERDL, Fort Belvoir, Virginia, April 1967.

[5] James A. Dennis, *Demolition of Post-Tensioned, Prestressed, Concrete Bridge Beams with High-Explosive Charges (Phase IV – Final Phase)*, Report 1959, USAMERDC, Fort Belvoir, Virginia, July 1969.

[6] James A. Dennis, *Comparison of Composition C-4 Explosive and M118 Demolition Charges (Detasheet C Explosive) for Military Demolitions*, Report 1900, USAERDL, Fort Belvoir, Virginia, June 1967.

— Were the test environments similar to the military environments in which the results are to be applied?

— Were the techniques employed by the test personnel standard to the military and set forth in the current FM 5-25?

(The first experimental data obtained used inputs from FM 5-25, October 1963. There have been two revisions (with formulae changes) since the first experimental data were obtained. The current copy of FM 5-25 is dated February 1971.)

— Are the support equipment and facilities utilized in the test program standard to the military and available in inventory?

— Were the explosives used in the test program standard military issue? Were the test explosive characteristics, density, detonating velocity, etc representative of those explosives in Army inventory?

Test data were obtained from beams which had been previously exposed to explosive charges. This is shown in Table 4 which shows that 429 explosive tests were conducted on 83 test-beam specimens. There may have been residual structural weakness in a beam as a result of prior explosions which could affect the concrete-steel bond strength, the structural integrity, and the structural-response pattern.

Further, the effective span length and the reaction configuration (ground bearing versus abutment bearing) are different for explosive tests subsequent to the tests when the element is acting as a simply supported beam. Also, a beam on piers or abutments has four air-concrete interfaces, while a beam on the ground would have three such interfaces plus a concrete-ground interface. A beam resting in contact with the ground reacts more like a footing or slab than like a structural beam when subjected to explosive forces.

13. **Experimental Data.** Table 4 shows the experimental/calculated values for the beams. Details of the experiments conducted on the four test-beam types are contained in the respective references cited herein. There is sufficient detail, data, and supporting discussion in the respective appendices of this study. The following paragraphs contain the results and conclusions for the four types of prestressed beams tested.

In the referenced test programs, the criterion for a successful demolition was that there be a complete breach of the concrete material from around the prestressing steel through the beam cross section. Severance of the steel strands or rods was not considered an important criterion.

Table 4. Test Beams/Explosive Charge Data (Composition C-4)

Prestressed Concrete Beam AASHO Type	No. of Beams Procured	Type of Explosive Charge	Number of Tests Performed	Charge Calculations (Vandersluis)[a] Top Breach	Charge Calculations (Reference FM 5-25) C_T Tamped	C_U Untamped	Multi-Charge	Experimental Test Data (lb) C_T	C_U
I	25	Pressure	24	(11)	16.2	21.6		17	25
		Bottom Breach	16			16.4			15
		Side Breach	39			4.4	1.75		1-7/8
		Linear Shaped	26	West German DM 19					19.8
				USAERDL Improvised					9.5
II	20	Pressure	15	(15)	30.4	40.4		30¼[b]	60[b]
		Bottom Breach	20			29.1			50
		Side Breach	40			5.3	1.5–2.1		2-5/8
		Shaped	30	M2A3					11.5
				M3					30
III	20	Pressure	10	(29)	54.1	72.1		75[b]	
		Bottom Breach	13			53.2			75
		Side Breach	72			13.8	5.3–5.9		3¼
Box	18	Pressure	27	(12)	22.1	29.6		15	22½
		Bottom Breach	24			20.2			15
		Shaped	17	Dual M2A3 Charges					23
				M3					30
			6	USAERDL Improvised Charges					13½

[a] Howard J. Vandersluis, *Hasty Demolition of Concrete Structures*, Technical Report 1663-TR, USAERDL, Fort Belvoir, Virginia, January 1961.

[b] Based on insufficient experimental data.

14. **Pressure Charge Experiments.** Table 5 shows the formulae which were derived for the four different Type AASHO beams. The averages of the pressure formula results are:

$$P = 0.00216H^2T \text{ (tamped)}$$
$$P = 0.00362H^2T \text{ (untamped)}$$

Table 5. Experimentally Derived Formulae

Beam Type AASHO	Tamped	Untamped
I	$P = 0.00207H^2T$	$P = 0.00322H^2T$
II	$P = 0.00208H^2T$	$P = 0.00389H^2T$
III	$P = 0.00262H^2T$	No Data
Box	$P = 0.00187H^2T$	$P = 0.00374H^2T$
Average	$P = \frac{0.00216H^2T}{K_{explosive}}$	$P = \frac{0.00362H^2T}{K_{explosive}}$

Note: H = height in in.
T = width of flange in in.
$K_{explosive}$ = effectiveness factor = k_e

The untamped-to-tamped ratio is 5 to 3 for the data versus the 4 to 3 ratio shown for the formulae in FM 5-25. If H and T are measured in feet, the formulae become:

$$P = \frac{3.72H^2T}{K_{explosive}} \quad \text{(tamped)}$$

$$P = \frac{6.25H^2T}{K_{explosive}} \quad \text{(untamped)}$$

The deviations between the constants shown in FM 5-25 and the experimentally derived data are shown in Table 6.

Table 6. Pressure-Charge Coefficients

Source	Pressure-Charge Constants	
	Tamped	Untamped
FM 5-25	3	4
Experiment Data	3.72	6.25
Variation from FM 5-25	+24%	+56%

15. **Bottom-Breach Experiments.** For all breaching calculations, the basic equation employed was:

$$P = 0.000579R^3KC$$

where

R = radius of the effective thickness of material to be removed.
K = material factor (Table 3-2, FM 5-25).
C = tamping factor (Figure 3-13, FM 5-25).
(to be determined from the experimental data)

In the bottom breach formula, R was taken to be the height of the beam; K was taken from FM 5-25, Table 3-2. Experimental values for C are shown in Table 7.

Table 7. Bottom-Breach Tamping Factor

Beam Type AASHO	Tamping Factor C	(Experimentally Derived)
I	1.6	
II	2.6	
III	2.4	
Box	1.1	
Average Value	C = 1.9	$P = \frac{0.0011R^3K}{K_{explosive}}$

16. **Top-Breach Experiments.** The top-breach coefficients were derived using the experimental data obtained for the untamped pressure charges (Table 8).

Table 8. Top-Breach Tamping Factor

Beam Type AASHO	Tamping Factor C	
I	2.9	
II	2.9	
Box	2.1	
Average Value	C = 2.6	$P = \frac{0.00151R^3K}{K_{explosive}}$

17. **Dual-Side-Breach Experiments.** The dual-side-breach experimental values are shown in Table 9.

Table 9. Dual-Side-Breach Tamping Factor

Beam Type AASHO	Tamping Factor C (combined for both flanges)	
I	2.1	
II	6.93	
III	1.58	
Average Value	C = 3.5	$P = \frac{0.00203R^3K}{K_{explosive}}$

18. **Shaped-Charge Experiments.** The German DM29 shaped charge did not cut the Type-I beam (the only test program in which it was evaluated). Table 10 shows the results of the shaped charges which were employed against the prestressed concrete beams. Some of the charges were from standard inventory, and those designated USAERDL were improvised by the test personnel. Only successful breaks are reflected in the table.

Table 10. Shaped-Charge Data

Beam Type AASHO	Shaped-Charge Designator	Weight of Explosive (lb)	Remarks
I	DM 19	19.8	(TNT/RDX = 49/51 Ratio)
	USAERDL-C	9.5–9.6 (C-4)	Optimum shaped charge placed on tension flange
II	M2A3	11½	Composition B or Pentolite effective when placed on either flange
	M3	30	
III	No test data realized		
Box	No test data realized		

It should be noted that the USAERDL-C shaped charge improvised in the laboratory represents a savings of about 5 to 6 pounds of explosive and the M2A3 charge, a savings of about 44 pounds of explosive when employed against the face of the tension flange (bottom).

19. **Experimental Data/FM 5-25 Comparisons.** Table 4 contains the results of the data gained experimentally and the calculation performed in accordance with FM 5-25. The correlation ranges from fair to excellent. The pressure charge data for Beam Types II and III reflect inadequate data sampling. Because the criteria adopted for a successful demolition was that the beam break completely and fall from the piers or abutments, the experimental formulae should render any structural element incapable of carrying its designed load even should it not be knocked off its abutments.

IV. STEEL-CUTTING, HIGH-EXPLOSIVE CHARGES

20. **General.** Steel-cutting formulae must be generally applicable to the many basic structural elements and fabricated forms, different material alloys, different methods of application of explosive, different material and structural response characteristics, and, in addition, to the military operational requirements. One should be cautioned, therefore, that if one, two, three, etc general formulae are defined for any given set of the characteristics mentioned above, there is no surety that application to another set of characteristics will insure a successful cut. The formulae, however, would represent the best available data for the *first-charge* application and should render the target element inoperable or unable to perform its design function even should it not be severed completely.

21. **Formula Parameters.** For operational use, the number of measurements to be made and the parameters which should be considered should be kept simple and to a minimum. The parameters which generally appear in the demolition formulae are shown in Table 11.

It is important to note that in the equations which are reduced to $P = K_{eq} A$ or $K_{eq} D$ or $K_{eq} D^2$, all of which could apply to a given element under the same conditions, that K_{eq} is not the same. Each would differ by a mathematical conversion factor relation $A = 0.7854D^2$. Other equation coefficient differences are a function of the units which are used to measure or define the relationship—each formula must define its units of measure.

22. **Test Data Factors.** The test data were obtained using paste explosives (non-standard, laboratory fabricated, Composition C-4, and EL506A-5, forerunner of Detasheet-C) for the following structural elements:

- Steel plates
- Structural steel—beams, angles, and channels
- Wire rope
- Bars—round and square
- Pipe

Table 11. Formula Parameters

Parameter	Symbol
Weight of explosive	P
Area	A
Diameter	D
(Diameter)^2	D^2
Equation Coefficient	K_{eq} = function (k_m, k_e, k_f, k_t, k_r, k_p, k_c, k_s)
Material Coefficient	k_m
Explosive effectiveness	k_e
Material form factor	k_f
Material toughness	k_t
Element reactance	k_r
Explosive placement	k_p
Coupling factors	k_c (coefficient coupling whose effects are $\gtrsim$ the mathematical values)
System probable error	k_s

Charge placements included offset, cross-fracture, saddle, and diamond-shaped applications. The German DM-19 and an improvised USAERDL linear-shaped charge were tested for their effect on steel plates. The basic unit of measurement is the inch for length and the pound for weight.

23. Experimental Test Data.

a. Steel Plate Tests:

$$P_{50\%} = \frac{0.075A}{k_e}$$

$$P_{100\%} = \frac{0.248A}{k_e}$$

$$P_{20\%} = \frac{0.038A}{k_e}$$

b. Structural Steel Angle:

$$P_{50\%} = \frac{0.108A}{k_e}$$

$$P_{100\%} = \frac{0.246A}{k_e}$$

$$P_{45\%} = \frac{0.094A}{k_e}$$

c. **Steel Beams:** $P_{50\%} = \frac{0.103A}{k_e}$

$P_{100\%} = \frac{0.150A}{k_e}$

$P_{8\%} = \frac{0.008A}{k_e}$

d. **Channels:** $P_{50\%} = \frac{0.074A}{k_e}$

$P_{max} = \frac{0.080A}{k_c}$

$P_{min} = \frac{0.070A}{k_e}$

e. **Wire Ropes:**

6x19, 1" Nominal O.D.: $P = \frac{0.73D^2}{k_e} = \frac{0.73D}{k_e}$

7x7, 1½" Nominal O.D.: $P = \frac{0.39D^2}{k_e} = \frac{0.59D}{k_e}$

24. Cross-Fracture Charge Techniques.

a. **Square Steel Rods:** $P_{50\%} = \frac{0.28A}{k_e}$

$P_{100\%} = \frac{0.33A}{k_e}$

$P_{37\%} = \frac{0.21A}{k_e}$

b. **Round Steel Rods:** These test data show a wide variance (The variance may be due to the conduct of the tests, the techniques used, or the explosive employed.) in correlation to the parameters A or D^2:

D = 2 and 3 inches

$$P_{50\%} = \frac{0.62D^2}{k_e}$$

$$P_{max} = \frac{0.93D^2}{k_e}$$

$$P_{min} = \frac{0.38D^2}{k_e}$$

D = 4 inches

$$P_{50\%} = \frac{0.22A}{k_e} = \frac{0.281D^2}{k_e}$$

$$P_{max} = \frac{0.33A}{k_e} = \frac{0.421D^2}{k_e}$$

$$P_{min} = \frac{0.12A}{k_e} = \frac{0.153D^2}{k_e}$$

Yielding general formulae:

$$P_{50\%} = \frac{0.45D^2}{k_e}\ ; \quad P_{max} = \frac{0.93D^2}{k_e}\ ; \quad P_{min} = \frac{0.15D^2}{k_e}$$

25. Cross-Fracture, Saddle Charge Techniques: Round Steel Bars. The tests (15 trials) were performed on steel bars with an O.D. = 2″, 4″, and 6″ from which

$$P = \frac{0.14D^2}{k_e} \text{ for all diameters.}$$

26. Diamond-Shaped Charge.

a. Round Steel Bars. The experimental test data were realized on steel bars with an O.D. = 2″, 3″, 4″, and 6″ from which the results shown in Table 12 were derived.

Table 12. Diamond-Shaped Charge Coefficients

	Parameter Correlation Coefficients		
(in.)	D	D^2	A
2	0.215	0.107	0.136
3	0.264	0.088	0.112
4	0.355	0.089	0.113
6	0.389	0.048	0.061
Average	0.306	0.083	0.106
	$P = 0.306D/k_e$	$P = 0.083D^2/k_e$	$P = 0.106A/k_e$

b. **Steel Pipe Charge.** The following data is based on two successful cuts in five trials on one pipe size tested:

$$P = \frac{0.253A}{k_e}.$$

27. **Linear-Shaped Charges: Steel Plate.** Shaped-charge data were realized from six German DM-19 and eight improvised USAERDL linear charges. The charges were employed against steel plates, and the size of the resultant crater was determined. The results are shown in Table 13.

Table 13. Linear-Shaped Charge Data

DM-19		Improvised USAERDL	
19.80 lb of explosive		5.02–7.80 lb of explosive	
Crater Volumes		Crater Volumes	
11.5 $in.^3$/lb	average	27.5 $in.^3$/lb	average
12.8	max	37.2	max
7.35	min	24.9	min

$$\frac{\text{Material removal effectiveness}}{\text{per pound explosive}} = \frac{\text{USAERDL}}{\text{DM-19}} = \frac{2.4 \text{ to } 3.3}{1}$$

V. TIMBER-CUTTING CHARGES

28. **Derivation.** The timber-cutting charge formulae were derived from 25 test charges for 6 species of trees with diameters ranging from 12.5 to 27.0 inches. There were 25 test trials: 13 successful tests, 6 incomplete cuts, and 6 marginal cuts. The explosives used were TNT, C-4, and Detasheet-C. Table 14 shows the results of the test data.

Table 14. Timber-Cutting Test Results

Coefficient	Explosive		
	TNT	DS-C	C-4
Mean Value	.0289	.0179	.0139
89% of cases	.0310	.0214	.0157
98% of cases	.0331	.0249	.0175
99% of cases	.0352	.0284	.0193

Note: General Formula $P_{50\%} = \frac{0.0289D^2}{k_e}$

$$P_{50\%} = \frac{0.00292}{k_e} c^2$$

Where c = circumference, inches.

VI. CONCLUSIONS

29. **Conclusions.** Based on the experimental data and the analyses presented in this report, the following conclusions may be stated:

a. Prestressed concrete bridge elements can be cut effectively with the standard military explosives TNT, Detasheet-C, and C-4; shaped charges; and improvised explosive pastes and linear-shaped charges.

b. From the weights of explosives required, based upon the *experimental environment,* the order of increasing quantities is:

(1) dual-side-breaching
(2) bottom face of tension flange (lower flange)
(3) top face of compression flange (upper flange)

The linear-shaped charges which were improvised at USAERDL required from 1/2 to 1/3 the amount of the bottom-breaching explosive charges. Dual-side-breaching charges attached to the top and bottom flanges of a beam required from 1/12 to 1/20 the amount of the untamped pressure charge and 1/8 to 1/12 the amount of the tamped pressure charge.

c. The prestressing steel elements need not be severed to achieve a successful cutting of the beam. Removal of the concrete in sufficient quantities at the critical cross section of the beam will cause failure.

d. Experimental values for prestressed concrete beams which reflect the mean or average of the data presented are used to define the following formulae where P = lb and linear measurements are in inches, and K from FM 5-25:

Untamped $$P = \frac{0.00362H^2T}{k_e}$$

Tamped $$P = \frac{0.00216H^2T}{k_e}$$

Bottom breach $$P = \frac{0.0011R^3K}{k_e} \quad (C = 1.9 \text{ from data})$$

Dual-side-breach $$P = \frac{0.00203R^3K}{k_e} \quad (C = 3.5 \text{ for both faces})$$

e. There exists a wide variance in results for steel cutting which renders any general formulae vulnerable to wide variations in effectivity. Both the data and analyses indicate that steel cutting is highly subjective. Some of the factors of importance which affect the results include:

- material
- explosive effectiveness factor
- target element form, geometry, and measurements
- material toughness characteristics
- target element reactance
- explosive placement
- coupling factors (ratios of explosive, target geometries)
- system error (normal variance if all the above are 1.0)

f. The standard military explosives and the USAERDL improvised pastes were effective for steel cutting. So were standard shaped and improvised USAERDL linear-shaped charges. The latter were 2 to 3 times as effective in steel cratering as was the German DM-19 charge.

g. Single formulae reflecting only D, D^2, and A as the parameters and which are based on the experimental data are not possible for application to steel cutting but are shown in Table 15 for illustration. Some of the values in Table 15 are based on an insufficient number of tests and insufficient samples for parameter range in size.

Table 15. Steel-Cutting Formulae (Experimental/FM 5-25)

Element	Steel-Cutting Formulae		
General Formulae from FM 5-25	Structural $P=.375A/k_e$	Other Steel $P=D^2/k_e$	Bars with $D<2''$ $P=D$
Plates	$P(100\%)=.248A/k_e$ $P(50\%)=.075A/k_e$		
Angles	$P(100\%)=.246A/k_e$ $P(50\%)=.108A/k_e$		
Beams	$P(100\%)=.150A/k_e$ $P(50\%)=.103A/k_e$		
Channels	$P(100\%)=.080A/k_e$ $P(50\%)=.074A/k_e$		
Wire Rope		$P(100\%)=.073D^2/k_e$ $P(50\%)=.056D^2/k_e$	$P(100\%)=.073D/k_e$ $P(50\%)=.066D/k_e$
Cross-Fracture Rods	$P(100\%)=.33A/k_e$ $P(50\%)=.28A/k_e$		
Cross-Fracture Rods		$P(100\%)=.93D^2/k_e$ $P(50\%)=.37D^2/k_e$	$P(100\%)=1.33D/k_e$ $P(50\%)=.98D/k_e$
Diamond Shape Rods	$P(50\%)=.092A/k_e$	$P(50\%)=.075D^2/k_e$	$P(50\%)=.215D/k_e$
Cross-Fracture Saddle Rods	$P(50\%)=.175A/k_e$	$P(50\%)=.14D^2/k_e$	$P(50\%)=.27D/k_e$
Steel Pipe	$P(50\%)=.253A/k_e$		
Average Values	$P(100\%)=.211A/k_e$ $P(50\%)=.145A/k_e$	$P(100\%)=.50D^2/k_e$ $P(50\%)=.16D^2/k_e$	$P(100\%)=.70D/k_e$ $P(50\%)=.383D/k_e$
Ratio of Experimental average maximum value to FM 5-25 formulae	0.56	0.50	0.70

h. There exists a strong correlation to size of the explosive, the relationship of charge dimensions (thickness of charge to width of the charge), and the relationship of explosive thickness to thickness of the material to be cut.

i. The shape of the explosive charge and its placement are critical for some structural steel forms and material thickness. The data indicate the effectiveness of the diamond-shaped charge.

j. Timber-cutting formulae derived from the experimental data are shown in Table 14 and include:

$$\left.\begin{aligned} P_{99\%} &= 0.0352D^2 = 0.00356c^2 \\ P_{50\%} &= 0.0289D^2 = 0.00292c^2 \end{aligned}\right\} \text{TNT}$$

The timber-cutting formulae show the best correlation between FM 5-25 calculations and the experimental test data.

VII. SUGGESTED FUTURE PLANS

30. Future Test Programs. The following programs should receive serious consideration by the group(s) responsible for Army Explosives/Demolition functions:

a. The respective formulae should be solved and placed in tables (similar to those shown in Appendix E, Tables E-1 through E-5). Dimensions employed should reflect the measurement which is employed in the field, e.g., if tapes are in feet and tenths, centimeters or inches, then tables and formulae should reflect these measurements to preclude errors of conversion by field personnel. The amount of field computation should be minimized if not eliminated.

b. Further test programs should be considered for the steel-cutting data. The programs should be designed to provide a wider range in parameter size, structural shapes, and alloys.

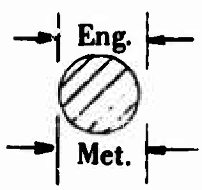
c. Future test programs should be designed for simple statistical analyses in order to provide better coefficient and parameter correlations.

d. Future test programs should be designed to realize data which reflect existing or required operational capability rather than USAMERDC test capabilities. The personnel capabilities, facilities, equipment, and procedures should be those available to the organic army unit charged with demolition responsibility.

e Only standard U. S. Army inventory explosives should be used for a test program until the factors and parameters relating to demolition are determined to a higher and better order of confidence than at present. Once the formulae are derived for the standard explosives, new explosives may be tested against them as a known base-line or reference.

f. Future test programs should include experimental analyses and verification of the formulae presented in this report as well as evaluation of the relationship of $P = 1.92 \times 10^{-2} \frac{L_E W_E T_M}{k_e}$ (which is derived in Appendix C and in computations shown in Table E-6, Appendix E). A very important parameter to be established in the test program is the error (or variation) assigned to testing (experimental error).

g. Because the explosives may be employed by personnel trained in either the metric or English units of measurement, the charge packages and formulae relating to weight should reflect number and tenths of standard packages rather than reference gram, kilogram, or pounds. One standard package will be manufactured for use in both systems and there should be no conversion required for weight charge regardless of the basic unit of measurement used, e.g.

Same Target	Equation	Same Standard Package
	Pounds = $k_{Eng}(in^2)$	Units and tenths of explosive package
	Kilograms = $k_{Met}(cm^2)$	

Eliminate any field application of conversions by marking the package in segments compatible for field operations and eliminate the weight in formulae, substituting the standard package (or segments thereof) in the formulae. Tables would appear as follows:

Metric Parameter	Explosive Charge	English Parameter
	Tenths of Package Number and tenths	

h. If as indicated by the analyses in this report that better parametric identification and refinement may be warranted, then a nomogram or a slide rule should be constructed to facilitate field or operational applications.

i. To keep language translation requirements to a minimum, graphic symbols and representative figures (standard cross sections, profiles, etc. such as

) should be utilized in place of description, supporting tables, etc. The graphic symbols should be established as an international standard much like the highway road signs which are employed internationally.

j. No test program should be permitted to conduct explosives/demolition field operations before the program test management plan (PTMP) has been accomplished and accepted by the program manager. As a minimum, the PTMP should contain the following:

- Objectives–basic and derived
- Test Performance Requirements and Acceptable Tolerances
- Method(s) of performance
- Resource Requirements–personnel, equipment, facilities, and procedures
- Milestones and schedule for resource requirements
- Preliminary analyses and predictions
- Supporting studies
- Supporting mathematical tables
- Supporting computer programs as applicable
- Parametric/error analytical update programs to adapt the experimentally derived data into the remaining test operations

Ideally, the field test experiments and test data analyses should proceed in parallel or at worst the analytical phase should lag by one operational day. Computer-assisted analyses may be warranted, but it would not be mandatory for a properly designed, adequately staffed, and controlled test program.

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An extensive bibliography is contained in Appendix B of TM 5-1300. Much effort has been expended in a joint task project relating to the design of structures to resist blast; some of the data should be pertinent to future analyses relating to demolition/high explosives.

GLOSSARY

Term	Meaning
Bonded construction	A structure capable of transferring axial force from the tendon to the beam concrete along the length of the tendon. Posttensioned beams are bonded by pumping grout into the space between the prestressing tendon and the sheath.
Breaching charge	An explosive charge which is used to break or shatter materials used in concrete slab bridges, bridge piers, bridge abutments, and field fortifications. Size, placement, and tamping or confinement are critical factors for creating a gap with a breaching charge.
Composite construction	A precast beam and a cast-in-place slab acting as one structural unit to resist loads in addition to those due to the beam and slab.
Compression	The force on a beam which tends to crush the beam toward its center.
Continuous beam	A beam uninterrupted over two or more spans and resting on three or more supports. Loads applied in one span produce stresses at all interior supports and in all spans.
Dead load	The weight of the bridge itself together with any fixed loads it may have to carry.
Deck bridge	A bridge on which the traffic moves entirely on top of the superstructures.
Demolition	The destruction of areas, structures, facilities, or materials. Military destruction employs fire, water, explosives, mechanical, or other means to accomplish a military objective.
Design load	The live load specified by design of the structure at working stresses.

Term	Meaning
Diaphragm	A transverse beam between stringers which serves to distribute loads to several stringers. End diaphragms are those at the ends of the stringers at the supports, and intermediate diaphragms are those in the span between supports.
Direct spalling	The dynamic disengagement of the concrete surface of an element resulting from a tension failure in the concrete normal to its free surface, caused by shock pressures of an impinging blast wave being transmitted through the element.
Final prestressing force	The force which remains in the prestressing tendons after all losses due to shrinkage, creep, and elastic deformation of the concrete; creep of the steel; friction between the tendon and the sheath (in posttensioned work); and inefficiency of the anchorage devices.
Flange	The wide parts of a structural beam (I-beam) or shape connected by the web.
High explosives	Substances which exhibit violent chemical reaction, going to a gaseous state at detonating velocities from 1000-8500 meters per second, producing heat and large volumes of gases which exert pressure upon the surrounding medium and a shattering effect upon a receiving target.
Impact load	The additional effect of the live load due to its speed.
Initial prestressing force	The load imparted to the prestressing tendons by jacking and before losses.
Live load	The weight of the traffic using the bridge.
Posttensioned	Prestressed concrete construction in which the prestressing steel is tensioned against the already hardened concrete.

Term	Meaning
Precast beam	A beam which is cast on the ground, either in a yard or at the job site, and then erected.
Pressure charge	An explosive charge which is used primarily for the demolition of simple span reinforced concrete T-beam and cantilever bridges. It is placed upon the bridge surface or roadway so that the explosive force acts in the direction of the bridge dead-weight causing shattering and spalling of the concrete and overloading at the weakened section.
Prestressed concrete	A method of construction which utilizes the high strength characteristics of steel strands and concrete by introducing stresses into the concrete member which are opposite to those which will occur from the dead load of the structure and the live load to be applied. The objective is to insure that the concrete will not sustain tensile forces at working loads.
Pretensioned	Prestressed concrete construction in which the prestressing steel is tensioned against temporary abutments and the concrete is then cast around the tensioned steel. After the concrete has hardened, the steel is released from the temporary abutments and its load transferred to the concrete.
Relative effectiveness factor	The relative shattering effect (brisance) of an explosive when compared to the shattering effect of TNT (1.00). It is related to its detonating velocity, density, and energy production.
Scabbing	The dynamic disengagement of the concrete surface of an element resulting from a tension failure in the concrete normal to its free surface, caused by large strains in the flexural reinforcement.
Shaped charges	An explosive charge designed to project its detonating action and energy in a more effective and concentrated pattern against a target.

Term	Meaning
Simple span beam	A beam of one span supported at the ends only.
Span	The distance between supports of a bridge. It may be the total distance or length of bridge from abutment to abutment or from abutment to intermediate ground support.
Strand	A prestressing tendon formed by twisting a number of individual wires together.
Tamping	The process of packing material around an explosive to contain or prevent loss of the explosive effect.

ABBREVIATIONS

A	cross-sectional area, square inches
AASHO	American Association of State Highway Officials
act	actual
ALCOA	Aluminum Company of America
AMCP	Army Materiel Command Pamphlet
avg	average
B	type of explosive
c	circumference
C	tamping factor
calc	calculated
cc	cubic centimeter
cm	centimeter
cps	cycles per second
D	diameter, inches
deg	degree of angle
E	modulus of elasticity
Eng	English system of measurements
eq	equation
exp	experimental data
f	frequency, cycles per second
F	force
FM	Field Manual (US Army)
fps	feet per second
ft	feet (also designated as ')
g	acceleration due to gravity
gm	gram
H	height, inches
I	moment of inertia
in.	inch (also designated as ")
$\underline{k}$	constant, factor or coefficient
K	material factor
K.E.	kinetic energy
$K_{eq.}$	equation constant
$K_{explosive}$ (k_e)	experimentally derived coefficient
K_{exp}	experimentally derived coefficient
L	length, inches
lb	pound
m	mass, slugs
max	maximum

met	Metric system of measurements
min	minimum
mps	meters per sec
N	number of charges
P	weight of explosive, pounds
PTMP	program test management plan
ρ	Density, slugs per feet^3
r	Poisson's ratio
R	radius of breach
s	distance
sec	second
SRI	Stanford Research Institute
t	time
T	thickness, inches
μ	micro ($=10^{-6}$)
USAERDL	United States Army Engineer Research and Development Laboratories (became USAMERDC)
USAMERDC	United States Army Mobility Equipment Research and Development Center (formerly USAERDL)
V	velocity, feet per sec
w	weight per unit length, pounds per foot
W	width, inches or feet

APPENDICES

APPENDIX A

DEMOLITIONS/EXPLOSIVES

1. Demolitions.

a. General:

When considering the demolition effectiveness of explosives for a structure or a structural element, one should be aware that variations which exist between the general demolition formulae and the available test data may be introduced by the following factors which are not reflected in the formulae:

(1) Failure to consider the parameters which are used in the basic flexural formula used for design of elements subjected to bending loads. (The basic flexural formula is shown in Appendix B.)

(2) No consideration of the elastic wave propagation in the structure/structural elements (pressure/rarefaction waves) or accounting for wave reflection, refraction, amplification, damping, etc which are a function of material and geometry of each target.

(3) No consideration for structural resonance in response to the magnitude and duration of the blast output. In addition to direct shattering and spalling of material, structural vibrations which could occur include:

- lateral vibrations in a beam
- longitudinal vibrations in the steel reinforcing rods or prestressing steel strands
- vibrations of the decking/roadway of a bridge structure acting like a plate

b. Wave Propagation:

The energy which must perform the work requirements for demolition results from the detonation of the explosive. Later sections of this appendix give the general characteristics of the explosives used in the prior test programs which produced the data used for this analytical study.

The explosive energy results in a shock wave which is propagated through the structural member and the air surrounding the member. Analysis of this shock wave and

the propagation of the wave energy is a complex study in itself. It is mentioned here to show that the velocity at which this shock wave is propagated is a function of the media (material) through which it passes.

The general wave equation for velocity through a solid is

$$V = \sqrt{E/\rho}$$

where E = modulus of elasticity
ρ = material density

The velocity through air at standard conditions is 1120-1150 feet/sec. The following table shows the velocities of wave propagation through concrete and steel and the values used in their determination:

Parameter	Media of Propagation		
	Concrete	Steel	Air
E	4.07×10^6 lb/in.^{2}	29×10^6 lb/in.^{2}	–
ρ	4.50 $\frac{\text{slugs}}{\text{ft}^3}$	15.2 $\frac{\text{slugs}}{\text{ft}^3}$	0.002378
V	11,420 ft/sec	16,520 ft/sec	1140 ft/sec
Ratios	$V_c/V_s = 0.79$	$V_s/V_c = 1.27$	$V_a/V_s = 0.0998$
	$V_c/V_a = 10.02$	$V_s/V_a = 14.49$	$V_a/V_c = 0.0692$

One should note that the effects of the shock wave are propagated at different velocities through the structural elements. The physics of wave phenomena which are a function of both the material and the geometry of the element include pressure and rarefaction waves, reflection, refraction, resonance, impedance, absorption, reinforcement, and cancellation. Again, it should be pointed out that these phenomena may have a greater effect in the demolition of some targets than do the parameters which appear in the general demolition formulae.

It should also be pointed out that there are degrees of structural behavior of the material used in the structural element. For reinforced concrete, the following may be listed:

– cracking of the concrete
– crushing of the concrete
– disengagement of the concrete from the reinforcing steel

The effects of the three degrees of structural damage listed above are not correlated to original load or design capacity of the structural element. The criterion used for structural demolition in the test programs which generated the data for this study was the disengagement of the concrete from the prestressing strands or rods and the dropping of the structural element from its piers, abutments, or reaction points.

Such a criterion could be designated as approaching absolute structural demolition—the element is physically and mechanically incapable of meeting any fraction of the design loading.

The following section introduces the considerations of structural vibration and element resonance. It must be pointed out that the initiating source of both the energy and the excitation frequencies for structural resonance is the explosive.

The response of the structural element can be expressed in two modes of structural behavior:[7]

(1) The *ductile mode* in which the element attains large inelastic deflections without complete collapse.

(2) The *brittle mode* in which partial failure or total collapse of the element occurs.

c. **Structural Vibration:**

The following relationships are introduced to show that there could be vibrations established in the structure and the structural elements which compose the demolition target. The following equations indicate the fundamental and harmonic (multiples) resonance frequencies which could affect the results of a test program as well as a field application. Should the structure or one of its critical elements be in a resonant condition as a result of the initial explosion, the destructive energy required should be much less than if resonance was not present. No detailed analyses are proposed because each demolition target is unique, and operational conditions do not permit the luxury of such analyses.

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[7] TM 5-1300, ***Structures to Resist the Effects of Accidental Explosions,*** Departments of the Army, Navy and Air Force, June 1969.

(1) Lateral Vibrations in Uniform Beams:

$$f_n \text{ (cps)} = c_n \sqrt{\frac{gEI}{wl^4}}$$

where:
E = modulus of elasticity, lb/in.^{2}
I = moment of inertia, in.^{4}
(EI = flexural stiffness, lb-in.^{2})
w = weight per unit length, lb/in.
l = length of beam, in.
g = 386 in./sec^2.
c_n = number depending on boundary conditions and mode number.

Beam Configuration	c_1	c_2	c_3	c_4	c_5
Simply supported ends	1.56	6.28	14.10	25.1	39.3
Clamped-free	0.56	3.57	9.82	19.2	31.8
Free-free or clamped-clamp	3.58	9.82	19.20	31.8	47.5
Clamped-hinged or hinged-free	2.45	7.96	16.60	28.4	43.3

(2) Longitudinal Vibration in Uniform Rods:

$$f_n \text{ (cps)} = c_n \sqrt{\frac{gAE}{wl^2}}$$

where:
E, g, w, and l are the same as in para. (1) above.
A = Cross-sectional area, in.^{2}
c_n = number depending on boundary conditions and mode number n.

End Conditions	c_n where n = 1, 2, 3 . . .
free-free or clamped-clamped	1/2 n
clamped-free	1/4 (2n-l)

(3) Vibration of Plates:

$$f_{mn} \text{ (cps)} = \frac{\pi}{2} \sqrt{\frac{gD}{hd}} \left(\frac{m^2}{a^2} + \frac{n^2}{b^2}\right)$$

where: m = 1, 2, 3, . . .

n = 1, 2, 3, . . .

a,b = dimensions of sides of plate

h = thickness of plates

d = weight per unit volume of plate material

D = $Eh^3/12(1 - r^2)$

r = Poisson's ratio

g, E are the same as in para. (1) above.

$\pi/2 = 1.57$

The above relationships can be found in the *Standard Handbook for Mechanical Engineers,* 7th Edition, McGraw-Hill, Inc. 1967 by Baumeister and Marks.

2. High Explosives (from TM 9-1300-214).[8]

a. **General.** During the past 100 years, many explosives have been studied for possible suitability for military use: yet, less than a score have been found acceptable for such use and some of these have certain characteristics that are considered to be serious disadvantages. Required characteristics are such that but few explosives can meet most of them and be acceptable for standardization.

b. **Availability and cost.** In view of the enormous quantity demands of modern warfare, explosives must be produced from cheap, raw materials that are nonstrategic and available in great quantity. In addition, manufacturing operations must be reasonably simple, cheap, and safe.

c. **Sensitivity.** All explosives are sensitive to some degree but can be too sensitive for handling and use or too insensitive for use. It may be considered that the present standard explosives represent a range of sensitivity within which a new explosive must fall.

d. **Brisance and power.** A military explosive must have shattering effect (brisance) and potential energy that make it comparable with or superior to other high explosives used as bursting charges; or it must have the ability to initiate the detonation of other explosives and be sensitive enough itself to be initiated by practicable means such as percussion, friction, flame, or electric current.

e. **Stability.** In view of the long periods of storage to which they are subjected during peace and because of the adverse conditions or storage to which they may be exposed, military explosives must be as stable as possible. Global warfare has increased

[8]TM 9-1300-214, *Military Explosives,* Departments of the Army and the Air Force, November 1967.

the variety of adverse conditions to which ammunition is exposed, and this has resulted in an increase in the requirements designed to prevent the harmful chemical and physical effects of such adverse conditions.

f. **Density.** Loading density is an important characteristic of a military explosive, a maximum density being desirable because of the fixed volume of the space available for explosives in a round of ammunition. The greater the loading density at which a fixed weight of a given explosive is pressed or cast, the greater is its effect when detonated. However, the standard explosives having the greatest density values, mercury fulminate and lead azide, are not the most powerful standard explosives; and the selection of an explosive for a specific use cannot be based primarily upon its density.

g. **Hygroscopicity.** Hygroscopicity, the property of absorbing moisture, can have an adverse effect on the sensitivity, stability, or reactivity of some explosives and must be negligible if the explosive is to be considered satisfactory for military use. An exception is the very hygroscopic ammonium nitrate, which can be used in the manufacture of amatols, if kept under conditions that preclude the absorption of moisture.

h. **Volatility.** Volatility of military explosives is an undesirable characteristic, and the explosives must not be more than very slightly volatile at the temperature at which they are loaded or at their highest storage temperature. Loss by evaporation, the development of pressure in rounds of ammunition, and separation of constituents of mixtures are sometimes the result of undue volatility.

i. **Reactivity and compatibility.** Minimum reactively and consequent maximum compatibility with other explosives and nonexplosive materials are necessary properties of a military explosive. As the explosive must be loaded in contact with metal or coated metal and may be mixed with another explosive or mixed with the other ingredients of a propellant, the explosive must be nonreactive therewith. Reaction, particularly in the presence of moisture, may produce sensitive metallic salts, cause deterioration and loss of power or sensitivity, or may result in the liberation of gaseous products of reaction. Compatibility is particularly important if the explosive is to be mixed with liquid TNT to make an explosive mixture suitable for loading by casting.

j. **Toxicity.** Many explosives, because of their chemical structures, are somewhat toxic. To be acceptable, a military explosive must be of minimum toxicity. Careful attention must be paid to this feature, because the effects of toxicity may vary from a mild dermatitis or a headache to serious damage to internal organs.

k. **Convenient** size and shape for packaging, storage, distribution, handling, and emplacement by troops.

l. High energy output per unit volume.

m. **Explosives Used for Demolition.** Table A-1 shows the characteristics of the principal explosives used in the U. S. Table A-2 shows the characteristics of standard military block demolition charges. The data relating to weight are used to establish explosive charge tolerances in Appendix E. The following table contains the unit weight of the explosives used in both the Metric and English systems of measurement:

Explosive	Unit Weight	
	Metric (gm/cc)	English (lb/in.^{3})
Composition C-4	1.57	0.0567
EL506A-5	1.48	0.0535
Paste Explosive	1.52	0.0548
TNT	1.56	0.0563
Conversion	$\frac{1}{27.7}$	$\frac{0.0361}{1}$

3. **Explosive Characteristics Tests.**

a. **Density Tests of C-4 and M118 Charges.** Ten 2½-pound blocks of C-4 explosive and ten ½-pound sheets of Detasheet C explosive from M118 charges were tested to determine the average densities for charges of these explosives used in this evaluation. The plastic wrappers of the C-4 blocks and the adhesive tape and protective paper of the Detasheet charges were removed before density determinations were made. Each explosive charge was first weighted and then submerged in a graduated beaker of water. The change in volume was recorded as the volume of the explosive charge. The explosive weights divided by the volume changes determined the densities for the explosive charges as shown in Table A-3. Simple mathematical analyses of the experimental data shown in Table A-3 indicates a standard deviation about the mean of ± 0.009 and ± 0.024 gm/cc for C-4 and Detasheet C, respectively.

b. **Rate of Detonation Tests.** Rate of detonation tests were performed on various size charges of C-4, Detasheet C, and TNT explosive to establish average velocities of detonations for the lots of these three explosives that were evaluated. An Electronic Counter Chronograph was used to measure the velocity of detonation for each of the charges. Two T-1 targets were slightly embedded 6 inches apart in the explosive charges, with the first target placed 5 inches in from the end of the charge where an M6 electric blasting cap was butted for initiation of the explosive. Upon detonation of the charge, the electronic counter recorded the time in microseconds for the detonation wave to travel through the explosive from the first target to the second one. Velocity of detonation of the explosive charge was calculated from the elapsed time recorded by the

Table A-1. Characteristics of Principal U. S. Explosives Used for Demolition Purposes

Name	Principal Uses	Velocity of Detonation (meters/sec) (feet/sec)	Relative Effectiveness as a Breaching Charge (TNT = 1.00)	Intensity of Poisonous Fumes	Water Resistance
Ammonium Nitrate	Demolition charge, and composition explosives.	2,700 mps, 8,900 fps	—	Dangerous	None
PETN	Detonating cord, blasting caps, and demolition charge.	8,300 mps, 27,200 fps	1.66	Slight	Excellent
RDX	Blasting caps, composition explosives.	8,350 mps, 27,400 fps	1.60	Dangerous	Excellent
TNT	Demolition charge, and composition explosives.	6,900 mps, 22,600 fps	1.00	Dangerous	Excellent
Tetryl	Booster charge and composition explosives.	7,100 mps, 23,300 fps	1.25	Dangerous	Excellent
Nitroglycerin	Commercial dynamites.	7,700 mps, 25,200 fps.	1.50	Dangerous	Good
Black powder	Time blasting fuse.	400 mps, 1,300 fps	0.55	Dangerous	Poor
Amatol 80/20	Bursting charge.	4,900 mps, 16,000 fps	1.17	Dangerous	Very poor
Composition A3	Booster charge and bursting charge.	8,100 mps, 26,500 fps	—	Dangerous	Good
Composition B	Bursting charge.	7,800 mps, 25,600 fps	1.35	Dangerous	Excellent
Composition C3	Demolition charge.	7,625 mps, 25,000 fps	1.34	Dangerous	Good
Composition C4	Demolition charge.	8,040 mps, 26,400 fps	1.34	Slight	Excellent
Tetrytol 75/25	Demolition charge.	7,000 mps, 23,000 fps	1.20	Dangerous	Excellent
Pentolite 50/50	Booster charge and bursting charge.	7,450 mps, 24,400 fps	—	Dangerous	Excellent

Table A-2. Characteristics of Block Demolition Charges

Nomenclature	Explosive	Weight	Size (inches)	Detonating Velocity (meters/sec) (feet/sec)	Relative Effectiveness Factor	Packaging and Total Weight
CHARGE, DEMOLITION: Block (TNT)	TNT	¼ lb	1½ D x 3½ L	6,900 mps, 22,600 fps	1.00	200 per wooden box, wt: 79 lb
		½ lb	1¾ x 1¾ x 3¾			96 per wooden box. wt: 65 lb
		1 lb	1¾ x 1¾ x 7			48, 50, or 56 per wooden box. wt: 80 lb
CHARGE, DEMOLITION: M2 block	75/25 tetrytol, w/tetryl booster.	2½ lb	2 x 2 x 11	7000 mps, 23,000 fps	1.20	8 per haversack, 2 haversack (16 chg) per wooden box. wt: 57 lb
CHARGE, DEMOLITION: M3 block.	Comp. C-2	2¼ lb	2 x 2 x 11	7,650 mps, 25,100 fps	1.34	8 per haversack, 2 haversack (16 chg) per wooden box. wt: 45 lb
	Comp. C-3			7,625 mps, 25,000 fps		
CHARGE, DEMOLITION: M5A1 block.	Comp. C-4	2½ lb	2 x 2 x 11¼	8,040 mps, 26,400 fps	1.34	1 per plastic bag, 24 bags (24 chg) per wooden box, wt: 80 lb
CHARGE, DEMOLITION: M112 block.	Comp. C-4	1¼ lb	1 x 2 x 11	8,040 mps, 26,400 fps	1.34	1 per plastic bag, 30 bags (30 chg) per wooden box. wt: 48 lb
CHARGE, DEMOLITION: M118 block.	PETN or RDX based.	Block: 2 lb Sheet: ½ lb	Block: 1¼ x 3¼ x 12½ Sheet: ¼ x 3 x 12	7,190 mps, 23,600 fps	1.14	1 block (4 sheets) per plastic wrapper, 20 blocks per wooden box. wt: 52 lb
CHARGE, DEMOLITION: M186 roll.	PETN or RDX based.	25 lb (½ lb per foot)	¼ in. x 3 in. x 50 ft	7,190 mps, 23,600 fps	1.14	1 roll per canvas bag, 3 bags per wooden box: wt: 115 lb
CHARGE, DEMOLITION: Ammonium nitrate.	Ammonium nitrate with TNT booster.	43 lb	7 D x 24 L	3,400 mps, 11,000 fps	0.42	1 metal container per wooden box. wt: 52 lb

Table A-3. Explosive Densities for 2½-Pound Blocks of C-4 and ½-Pound Sheets of Detasheet C

Sample	C-4			Detasheet C		
	Weight (gm)	Volume (cc)	Density (gm/cc)	Weight (gm)	Volume (cc)	Density (gm/cc)
1	1145	720	1.590	213	146	1.459
2	1143	719	1.589	218	156	1.397
3	1143	721	1.585	222	154	1.442
4	1145	720	1.590	218	151	1.444
5	1130	705	1.602	220	152	1.447
6	1129	709	1.592	229	158	1.449
7	1129	705	1.601	227	152	1.493
8	1153	733	1.572	228	154	1.481
9	1150	725	1.586	226	156	1.449
10	1123	711	1.579	222	153	1.450
Mean	1139	716.8	1.589	222.3	153.2	1.451
Standard Deviation of Density:			± 0.009			± 0.024

electronic counter. The rates of detonation for each explosive charge were calculated from the equation: $V \text{ (fps)} = \frac{dx10^6}{t}$, where V is the velocity of the detonation wave in feet per second, t is the time reading of the electronic counter in microseconds, and d is the separation distance of the targets in feet. Details and results of the rate of detonation tests were as follows:

c. **Rates of Detonations for Blocks of TNT and C-4 Explosives.** Seven M5A1 blocks of C-4 explosive and seven TNT explosive charges formed from ½-pound TNT blocks were tested to determine their velocities of detonations. The C-4 explosive was the military standard block with the plastic wrapper removed, but the TNT charges consisted of four, ½-pound TNT blocks butted end to end and taped together. Table A-4 gives the charge details and resulting rates of detonations.

d. **Rates of Detonations for Thin C-4 and Detasheet C Explosives.** Rate of detonation tests were conducted with C-4 and Detasheet C explosive charges of ¼ by 1 by 12 inches and ½ by 1 and 12 inches to establish the average velocities of detonations for these thin charges commonly employed for demolition of steel and timber. Composition C-4 explosive charges were cut from M5A1 demolition blocks without disturbing the explosive density. The Detasheet C explosive charges were cut from the ½-pound sheets of M118 demolition charges; the ½-inch-thick Detasheet C charges were

Table A-4. Rates of Detonations for Blocks of C-4 and TNT

M5A1 Blocks of C-4 Explosive				Charges Formed with ½-Pound Blocks of TNT Explosive			
Dimensions (in.)	Weight (lb)	Time Lapse (μ sec)	Rate of Detonation (fps)	Dimensions (in.)	Weight (lb)	Time Lapse (μ sec)	Rate of Detonation (fps)
2x2x10-11/16	2½	20.3	24,631	1-3/4x1-3/4x13-3/16	2	20.9	23,923
2x2x10-11/16	2½	19.9	25,126	1-3/4x1-3/4x13-3/16	2	21.0	23,810
2x2x10-3/4	2½	19.6	25,510	1-3/4x1-3/4x13-3/16	2	21.2	23,585
2x2x10-3/4	2½	18.7	26,738	1-3/4x1-3/4x13-3/16	2	20.9	23,923
2x2x10-11/16	2½	19.4	25,773	1-3/4x1-3/4x13-3/16	2	21.3	23,474
2x2x10-3/4	2½	19.7	25,381	1-3/4x1-3/4x13-3/16	2	21.0	23,810
2x2x10-11/16	2½	19.2	26,041	1-3/4x1-3/4x13-3/16	2	20.9	23,923
		Mean	25,600			Mean	23,778
		Std. Deviation	± 426			Std. Deviation	±167

made by sticking one, ¼-inch-thick sheet on top of another. Measured rates of detonations for these tests are given in Table A-5.

Table A-5. Rates of Detonations for ¼- and ½-Inch-Thick C-4 and Detasheet C Charges

Charge Dimensions (in.)	C-4 Explosive Weight (gm)	Time Lapse (μ sec)	Velocity of Detonation (fps)	Detasheet C Explosive Weight (gm)	Time Lapse (μ sec)	Velocity of Detonation (fps)
1/4x1x12	86	20.1	24,876	78	21.4	23,364
1/4x1x12	84	20.9	23,923	78	21.3	23.474
1/4x1x12	85	20.5	24,390	76	21.7	23,041
1/4x1x12	85	20.3	24,631	79	21.7	23,041
1/4x1x12	83	20.1	24,876	78	21.9	22,826
		Mean	24,539		Mean	23,149
	Standard Deviation		± 590	Standard Deviation		± 363
1/2x1x12	154	19.4	25,773	153	21.9	22,826
1/2x1x12	159	20.9	23,923	153	21.9	22,826
1/2x1x12	157	20.1	24,876	159	21.7	23,041
1/2x1x12	160	20.0	25,000	155	21.5	23,256
1/2x1x12	155	20.0	25,000	160	21.0	23,810
		Mean	24,914		Mean	23,152
	Standard Deviation		±590	Standard Deviation		±363

e. Rates of Detonations for Laminated Detasheet C Charges with Butt Joints. Rate of detonation tests were made on 10 Detasheet C explosive charges to determine the effect of the 1/32-inch-thick adhesive tape on laminated charges of stacked ¼-inch-thick sheets of the explosive and the effect of butt joints on charges with sheets of explosive butted together. The five laminated charges consisted of 48 pieces of 1-inch-square by ¼-inch-thick explosive stacked one on top of another to form 12-inch-long charges of 1-inch-square cross sections. The five charges with butt joints were ½ inch thick by 1 inch wide by 12 inches long and had three pieces of explosive that were ¼ inch thick by 1 inch wide by 4 inches long in the bottom layer on top of which were four pieces of explosive ¼ inch thick by 1 inch wide by 3 inches long; hence, there were two butt joints in the explosive charge between the target stations of the electronic counter that measured the velocities of the detonation waves. Table A-6 shows these measurements.

Table A-6. Rates of Detonations for Detasheet C Charges with Laminated Layers and Butt Joints

Explosive Dimensions (in.)	Explosive Weight (gm)	Time Lapse (μ sec)	Velocity of Detonation (fps)
	With Laminated Layers		
1x1x12	350	24.7	20,243
1x1x12	348	25.3	19,763
1x1x12	320	24.3	20,576
1x1x12	336	22.7	22,026
1x1x12	336	22.2	22,624
		Mean	21,046
		Standard Deviation	±1092
	With Butt Joints		
1/2x1x12	157	21.9	22,826
1/2x1x12	157	21.0	23,810
1/2x1x12	167	21.9	22,826
1/2x1x12	163	21.9	22,826
1/2x1x12	163	21.9	22,826
		Mean	23,023
		Standard Deviation	± 393

f. **Synopses of Explosives Characteristics Tests.** The following values were determined from the experimental test program for TNT, Detasheet C, and Composition C-4. The single value shown for Detasheet-C reflects the effects of size, packaging, thickness, laminated layers, and butt jointing of standard charges. The single value for Composition C-4 reflects the size and thickness effects:

TNT	Mean detonation velocity	= 23,778 fps
	Standard deviation	= ± 167 fps
C-4	Mean detonation velocity	= 25,086 fps
	Standard deviation	= ± 711 fps
	Mean density	= 1.589 gm/cm^3
	Standard deviation	= ±0.009 gm/cm^3
Detasheet-C	Mean detonation velocity	= 22,592 fps
	Standard deviation	= ±1088 fps
	Mean density	= 1.451 gm/cm^3
	Standard deviation	= ±0.024 gm/cm^3

Examination of the test results and the explosive characteristics in literature (AMCP 706-177) indicates that the experimental error due to the explosive characteristics and the test techniques used should be within ± 5% for the mean-detonation velocity and ± 3% for the mean density for the standard demolition explosives. The 5% deviation in mean-detonation velocity which could occur manifests itself in the kinetic energy (K.E.) which results from the explosion, e.g.

$$\text{Nominal velocity} = 25{,}000 \text{ fps} \pm 5\% = \frac{26{,}250}{23{,}750} \text{ fps variance}$$

$$\text{K.E. ratio} = \frac{(2625)^2}{(2375)^2} = \frac{\text{max}}{\text{min}} = 1.221 \text{ which is } \alpha \text{ explosive weight.}$$

The most probable kinetic-energy variation for the explosive would approximate a ±11% effect for the charge calculations shown in Section III of the main body of this report and would be a good first estimate for $\underline{\Delta EE}$ in the probable deviation relationship.

4. Test Explosive Characteristics.

a. Composition C-4 Explosive. Composition C-4, an RDX base plastic explosive, is white and has a density of about 1.59 grams per cubic centimeter as issued in a standard 2- by 2- by 11-inch block weighing 2½ pounds and designated Charge, Demolition, Block M5A1. In prior USAERDL tests, the detonating velocity of Composition C-4 explosive in M5A1 demolition blocks of the same lot as that used in the test program was shown to be 26,000 feet per second at a density of 1.57 grams per cubic centimeter. Composition C-4 explosive is about a third more powerful than TNT, and although blocks of C-4 explosive are semirigid, the explosive is plastic and can be molded into almost any shape. Molding or kneading of Composition C-4 explosive reduces its density with resulting reduction in its detonating velocity. Reduction of its detonating velocity also reduces its shattering power which significantly decreases its cutting or breaching effectiveness. Thus, when the weights and dimensions of the C-4 explosive charges for test shots varied from those of the 2½-pound, 2- by 2- by 11-inch blocks, to provide experimental control, a knife was used to cut the C-4 explosive blocks to the specified sizes to minimize disturbance of explosive density. The ingredients of Composition C-4 explosive are:

Ingredients		Percentage
RDX		91.00
Polyisobutylene		2.10
Motor Oil		1.60
Di-(2-ethylhexyl) Sebacate		5.30
	Total	100.00

b. **Paste Explosive.** The RDX base paste explosive used in this test program was manufactured by mixing bulk Composition C-4 explosive with DNT and MNT oils and Shell 40 thinner. It was a semifluid, oily explosive paste which had a density of 1.52 grams per cubic centimeter and a consistency of a light grease. The explosive and thinner oils exuded rapidly from the paste explosive and formed a pool on top of the explosive in the containers. For demolition of concrete, steel, and wooden targets, the explosive adheres more readily to the target surfaces if the oils are poured off prior to stirring of the paste explosive. The detonating velocity of the paste explosive used in these tests was determined by an electronic counter chronograph method on 10 explosive samples 1 by 1 by 18 inches. The average rate of detonation for the samples was 24,466 feet per second. The dull yellow paste explosive had ingredients as follows:

Ingredient	Percent of Paste Explosive
RDX	76.44
DNT	4.89
MNT	3.26
Shell 40 Thinner (Tween)	7.85
Polyisobutylene	1.74
Motor Oil	1.36
Di-(2-ethylhexyl) Sebacate	4.46
Total	100.00

c. **Aluminized Paste Explosive.** Paste explosive was aluminized by adding 18 percent by weight of ALCO 120 atomized aluminum powder. The aluminum powder and paste explosive were intermixed at the field test site by dumping the two ingredients together in a wooden mortar box (no metal parts) and blending the compound with a hoe until a uniform mixture was obtained. Density of the aluminized paste explosive was slightly higher than that of paste explosive because much of the oil was apparently absorbed by the finely divided aluminum powder; absorption of the oils adversely affected the adhesive characteristic of the explosive. Aluminized paste explosive was less plastic than paste explosive. However, because the aluminized paste explosive was less plastic than the paste explosive, slight tamping was required to form compact charges. In 10 rate-of-detonation tests in which an electronic counter chronograph method was used on 1- by 1- by 18-inch explosive samples, the average detonating velocity of the aluminized paste explosive was 23,079 feet per second or about 1,400 feet per second less than the detonating velocity of paste explosive. With a slower rate of detonation than paste explosive, the aluminized paste explosive had less shattering ability and was, therefore, less effective for steel cutting. After statistical analysis of experimental data from a factorial experiment had revealed that aluminizing the paste explosive did not increase its steel-cutting ability, the aluminized paste explosive was not evaluated further for cutting steel.

d. **Detasheet A Flexible Explosive.** A commercial formulation designated "Detasheet A" by its developer, this flexible sheet explosive, which was compared with Detasheet C explosive in this program, is composed of an integral mixture of 85 percent PETN and elastomeric binder that gives it flexibility and formability over a temperature range of 0° to 130° F. The 10- by 20-inch sheets of explosive are 0.207 inch thick with a density of 1.48 grams per cubic centimeter, or 5 grams explosive weight per square inch, and have a detonating velocity of 23,616 feet per second. Colored red for identification, Detasheet A explosive is consistently detonated with the U. S. Army special blasting caps; J-1 nonelectric, J-2 electric, and M6 electric, the standard overhand knot in a 10-inch bight of detonating cord also reliably explodes the sheet explosive. A knife was used to cut the sheet explosive to the desired configurations, and multiple sheets were stacked vertically to obtain a desired charge thickness. Detasheet A explosive was developed specifically for the velocity-impact hardening method of work-hardening castings made from manganese steel.

e. **TNT Explosive.** Trinitrotoluene, commonly known as TNT, is a light-yellow-colored high explosive having a detonating velocity of about 21,000 feet per second at a density of 1.56 grams per cubic centimeter. TNT is issued for general demolition use in 1/8-, 1/2-, and 1-pound blocks of cast explosive. Although TNT explosive is not exploded by the impact of a single rifle bullet, concentrated fire from automatic weapons may detonate it. About a third less powerful than Composition C-4 explosive for cutting steel and timber or breaching concrete, rock, or masonry, TNT explosive is used by the U. S. Army as base unity for comparison of the relative effectiveness of all other military high explosives as external demolition charges. Unpackaged 1/2-pound TNT explosive blocks of 1-3/4 by 1-3/4 by 3-5/16 inches were removed from the 1-pound container and used for comparison with C-4 and Detasheet C explosives as contact charges for concrete breaching and timber cutting. Individual blocks of TNT were taped together to form concrete-breaching and tree-cutting charges having contact surfaces as nearly similar as possible to those of the other test explosives.

f. **Detasheet C Flexible Explosive.** Detasheet C is the manufacturer's name for the flexible sheet explosive issued by the U. S. Army as the M118 demolition charge. The military standard M118 demolition charge consists of four stacked 1/4- by 3- by 12-inch sheets of Detasheet C explosive (Flex-X) of 2 pounds total weight packaged in a Mylar container. Each sheet contains 1/2 pound of Detasheet C explosive faced with an adhesive tape on one 3-inch-wide surface; a removable paper cover protects the adhesive tape. Detasheet C explosive is composed of an integral mixture of 63 percent PETN (pentaerythritol tetranitrate) and 8 percent pyrocellulose (a form of nitrocellulose), plasticized with acetyl tributyl citrate binder which gives it flexibility and formability over a temperature range of minus 65° to 160° F. With a density of 1.48 grams per cubic centimeter, the 1/4- by 3- by 12-inch sheets of Detasheet C explosive were said by the manufacturer to have a detonating velocity of 22,960 feet per second. The

explosive is pea green in color and can be reliably detonated by the U. S. Army special blasting caps or the standard detonating cord knot. The M118 demolition charges can be safely cut to smaller widths and lengths with a knife. The ingredients of Detasheet C explosive are:

Ingredients		Percentage
PETN		63
Pyrocellulose		8
Acetyl Tributyl Citrate Binder		29
	Total	100

g. **EL506A-5 Detasheet Flexible Explosive.** A commercial formulation designated "Detasheet" by its developer, the flexible-sheet explosive tested in this program was composed of an integral mixture of 85 percent PETN (pentalrythritol tetranitrate) and elastomeric binder that gave it flexibility and formability over a temperature range of 0 to 130° F. The 10- by 20-inch sheets of explosive were 0.207 inch thick with a density of 1.48 grams per cubic centimeter, or 5 grams explosive weight per square inch, and had a detonating velocity of 23,616 feet per second. Colored red for identification, the EL506A-5, flexible-sheet explosive was consistently detonated with the U. S. Army special blasting caps: J-1 nonelectric, J-2 electric, and M6 electric; the standard overhand knot in a 10-inch bight of detonating cord also reliably exploded the sheet explosive. A fixed-blade knife was used to cut sheet explosive to the desired configurations, and multiple sheets were stacked vertically to obtain a desired charge thickness. Detasheet flexible explosive of the EL506-A type tested was developed specifically for the velocity-impact hardening method of work-hardening castings made from manganese steel.

h. **Shaped-Charge Experiments.** Military standard conical-shaped charges were evaluated for explosive demolition of prestressed concrete box beams. Conical-shaped charges were evaluated for breaching both single and multiple box beams, but linear-shaped charges were tested only for cutting single box beams. Evaluation of shaped charges for demolition of prestressed concrete box beams laid as in simple span bridges was conducted as follows:

Test Procedures. Both linear- and conical-shaped charges, upon detonation, form high-velocity jets of liner particles from the collapse of metal or glass liners of lined cavity charges; hence, it was expected that high-explosive shaped charges detonated against either the top or bottom of the sides of box beams would cut many of the 19 steel stressing strands, detension the others, and breach the concrete through the entire cross section so that the severed beam would fall into the bridge gap The military standard M2A3 shaped charge with a 60-degree, glass-lined conical cavity and 11½

pounds of Pentolite explosive was tested for demolition of single and multiple beams from both the top and the bottom surfaces of the sides of the box beams. M2A3 shaped charges were detonated at the normal standoff of 5½ inches for demolition of box beams from the bottom, but 1- to 5½-inch standoffs were used to evaluate these charges for demolition of box beams from the top. Because their overall 40-pound weight made emplacement from the bottom difficult and time consuming, the M3 shaped charges with 60-degree, steel-lined conical cavities and 30 pounds of Composition B explosive were evaluated at 0- to 15-inch standoffs for demolition of the box beams from the top only, which required setting the charge in the correct position with no fastening. The USAERDL-fabricated, linear-shaped charges were investigated by being simultaneously detonated in multiples of two against the bottom surface of the two sides of single box beams because similar experiments on prestressed concrete I-beams had shown that employment to be optimum for these charges. Detonated at 4- to 6-inch standoffs from the box beams, the linear-shaped charges with half-round copper liners of 4- to 6-inch widths and 8-inch lengths were loaded with 4¾ to 6¾ pounds of hand-tamped C-4 explosive. Table A-7 lists the detailed design characteristics of conical- and linear-shaped charges evaluated.

Evaluation of conical- and linear-shaped charges involved fastening and detonating the charges against the top and bottom surfaces of the sides of the prestressed concrete box beams and measuring their destructive effects. A powder-actuated stud driver, a military standard demolition tool, was used to fasten the shaped charges to the bottom surfaces of the box beams. Conical M2A3 shaped charges were wired to rivet fasteners that were embedded into the bottom surface concrete of the box beams by the powder-actuated driver; fiberboard standoff sleeves issued with the shaped charges provided the 5½-inch standoff from the bottom of the sides of box beams. M2A3 and M3 conical-shaped charges detonated to breach the box beams from the top surface were simply set in place over the center of the two sides of single box beams or the center of the two exterior sides and the junction of the two adjoining sides of two adjacent box beams, requiring no fastening. Similarly, on the bottom surface of the box beams, the M2A3 shaped charges were emplaced with the center of the conical-shaped hollow cavity aligned opposite the center of the 5-inch-thick sides of single box beams and the exterior sides of two adjacent beams with a third shaped charge opposite the junction of the two adjoining sides of adjacent box beams. Evaluated for demolition of single box beams from the bottom, linear-shaped charges were emplaced with the linear cavity perpendicular to the long axis of the beams against the bottom of the two sides. Two flanged plates on the linear-shaped charges provided the correct target standoff and served as the base for riveting the charges to the concrete beams with the powder-actuated driver. The previously described detonating cord priming assemblies for pressure and breaching charges were used to ensure simultaneous detonation of two shaped charges for cutting single box beams and three charges for demolishing two adjacent beams.

Table A-7. Characteristics of Shaped Charges Evaluated

Type of Charge	Total Weight (lb)	Explosive Weight (lb)	Type of Explosive	Standoff Distance (in.)	Charge Diameter (in.)(a)	Charge Height (in.)	Container Material	Linear or Cone Liner			
								Material	Thickness (in.)	Angle (deg)	Outer Diameter (in.)(b)
M2A3	15	11-1/2	Composition B or Pentolite	5-1/2	6	9-7/15	Fiber	Glass	0.350	60	4-7/8
M3	40	30	Composition B or Pentolite	15	9-1/2	15-1/2	Sheet Metal	Steel	0.150	60	9
LC-1	9-1/4	5	C-4	4	4-1/8	9	Sheet Metal	Copper	0.125	Half round	4
LC-2	12-3/4	6-3/4	C-4	6	6	12	Sheet Metal	Copper	0.125	Half round	6
LC-3	8	4-3/4	C-4	4	4	9	Sheet Metal	Copper	0.062	Half round	4
LC-4	11-1/2	6-3/4	C-4	6	6	12	Sheet Metal	Copper	0.080	Half round	6
LC-5	10-3/4	6-1/2	C-4	6	6	12	Sheet Metal	Copper	0.062	Half round	5-7/8

Note: Weight of the fiber material was 1.7 pounds; weight of the sheet metal material was 5.6 pounds.

(a) Width of linear-shaped charges.
(b) Width of half-round copper liner of linear-shaped charges.

i. **Description of Test Linear-Shaped Charges.** The charges evaluated were two, standard, linear-shaped charges of the West German Army and a USAERDL-improvised, linear-shaped charge. These charges are described in the following paragraphs.

(1) **German Army Linear-Shaped Charge DM 19.** The DM 19, linear-shaped charge, a standard demolition material of the West German Army, weighed 39.16 pounds and contained 19.8 pounds of TNT/RDX explosive in a 49/51 percent ratio. The explosive was cast into a sheet metal container having a hemispherical copper liner at one end and a threaded capwell for priming the charge at the other end; another threaded capwell was located at one end of the charge near its top. These capwells would receive both the German electric and nonelectric blasting caps with priming adapters and U. S. Army standard blasting caps, although the thread prevented the use of U.S. Army priming adapters. The 8-inch-long, 9-inch-wide, half-round, copper liners gave the linear-shaped charge its high velocity, jet-forming capability. Two sliding sheet metal plates fastened in grooves on the sides of the charge provided a 10-inch standoff distance when fully extended. The charge had two holding clamps and two screws for connecting two charges, and any number of charges could be connected to form a linear-shaped charge of any desired length by using the issue sheet metal tie plates that could be riveted to the sides or bottoms of bridges. One cap could be used to detonate one end of a line of the shaped charges. According to a German Army manual, this charge was capable of cutting 78.74 inches of unreinforced concrete, 29.53 inches of reinforced concrete, and 11.81 inches of steel, with the cut being equal to the length of the charge. If two charges were placed and detonated diametrically opposite each other from both sides of the target, the depth of cut could be doubled. Each DM 19 shaped charge was packed separately in a wooden frame, and the complete package could be carried by a strap provided on the charge.

(2) **German Army Linear-Shaped Charge DM29.** The DM 29 linear-shaped charge consisted of 4.4 pounds of TNT/RDX explosive cast into a sheet metal container weighing 11 pounds overall. It was also a standard demolition material of the West German Army. An 8-inch linear, hemispherical, copper liner at one end of the charge gave it a high-speed, jet-forming capability when detonated by a blasting cap inserted in the single capwell at one end of the charge near the top. When extended, two sliding metal plates fastened to the sides of the charge provided a 5-inch standoff distance for detonation of the charge against steel or concrete targets. The DM 29 linear-shaped charges were said to be capable of cutting 31.49 inches of unreinforced concrete, 15.75 inches of reinforced concrete, and 5.90 inches of steel. Sheet metal tie plates and fastenings integral to the charge permitted the connection of multiples of the charges to form a linear-shaped charge of any desired length. Two DM 29 shaped charges were packed in a wooden frame.

(3) **Improvised Linear-Shaped Charges.** The linear-shaped charges designed by USAERDL were improvised from 21-gage sheet metal and 1/8 and 3/16 inch sheet

copper; Composition C-4 explosive was used as the explosive filler. The sheet metal containers were 8 inches long by 4-5/16 to 6-1/2 inches wide and had 8-inch, half-round linear copper liners soldered into one end to give the charges a high-velocity, jet-forming capability. Two flanged plates attached to the sides of the charges provided the correct standoff distances and served as the base for riveting the charges to the target with a rivet-punching, powder-actuated driver. Composition C-4 explosive was handloaded into the charge containers on top of the liners to heights of 3 to 5 inches above the liner apexes. Fifteen-gram PETN boosters embedded in the top and one side of the explosive column insured detonation when initiated by U. S. Army special electric blasting caps.

APPENDIX B

PRESTRESSED CONCRETE BEAM DATA

References:

(1) *Tentative Standards for Prestressed Concrete Piles, Slabs, I-Beams and Box Beams,* AASHO, Washington, D.C., March 1963.

(2) *Interim Specifications,* AASHO Committee on Bridges and Structures, Washington, D.C., 1971.

1. **Basic Flexural Formula.**

The basic relationship utilized in the design and investigation of structural members is the following:

$$\sigma = \frac{Mc}{I} \qquad \text{where}$$

σ is the Unit Stress (tensile or compressive) on any fiber, usually the most remote from the neutral surface (pounds/inch^2)

The unit stress permitted in the design is a function of the material used for the structural member.

M is the bending moment to which the member is subjected (pounds-inches)

The bending moment is a function of the load on the member, the method of support, the point of load application, and the length of the member. In designing to AASHO specifications for prestressed beams, the ultimate load capacity shall not be less than

1.5 (dead load) + 2.5 (design live load and impact load).

If the member were to fail by overload, it should be noted that the effect of the explosive energy should be greater than 0.5 (dead load) and 2.5 (design live load and impact load). This loading would have to be applied at the most critical cross section of the structural member with the energy supplied by the explosion.

c is the distance from the neutral surface to the fiber for which σ is established (inches).

I is the moment of inertia of the structural cross section with respect to its neutral axis (inches^4).

The last two members of the formula are a function of the geometry of the structural member. In any demolition operation, the effect of overloading is accentuated by shattering and spalling of the concrete material which in turn reduces the load capacity by reducing both the moment of inertia and the distance to the most extreme fiber when concrete material is removed from the critical, cross-sectional area of the structural member.

Stiffness of Structural Element.

The stiffness (k) of a simply supported structural element is equal to the following at the element midpoint:

$$k = \frac{48EI}{l^3} \qquad \text{where}$$

k = stiffness factor
E = modulus of elasticity
I = the modulus of inertia
l = the length of the element between supports

2. Prestressed Concrete Beams.

Four separate experimental programs were conducted on prestressed beams which were designed and fabricated to AASHO standards. Table B-1 shows the number of beams, their length, and the AASHO types which were procured for testing.

Table B-1. Concrete Beam Test Specimen

Type (AASHO)	Length (ft)	Number Procured	Figure
I	30	25	B-1
II	30	20	B-2
III	30	20	B-3
Box Beam	30	18	B-4

The following paragraphs of this appendix contain more detail about the prestressed concrete beams used in the experiments and the geometry of the beam test setup used in the experiments.

a. **Description of Type-I, Prestressed Concrete Bridge Beams.** Twenty-five, standard, AASHO-type-I prestressed concrete bridge beams of 30-foot length were used as the test structures for the explosive demolition experiments. These beams were one of four types of I-beam cross sections standardized by the Joint Committee of the American Association of State Highway Officials and the Prestressed Concrete Institute for prestressed concrete bridges with spans of 35 to 90 feet and were designed and constructed to AASHO standard specifications as listed in "Standard Plans for Highway Bridges"; Drawing Sheet Number 403, for 24-foot roadway.[9] The beams were precast at a Winchester, Virginia, prestressed concrete plant during early August 1964, using steel forms and steam curing, and were transported to the test site by truck on 9 September 1964.

Constructed of 5,000-psi, compressive-strength concrete pretensioned with eighteen 7/16-inch-diameter steel stressing strands, the prestressed I beams of 28-inch overall depth have a cross-sectional area of 276 square inches consisting of a 12-inch-wide by 7-inch-deep top (compression) flange, an 11-inch-deep by 6-inch-thick web, and a 16-inch-wide by 10-inch-deep bottom (tension) flange (Fig. B-1). Fourteen of the eighteen steel stressing strands, of the seven-wire type having a center wire enclosed tightly by six helically placed outer wires, were located on 2-inch centers in the bottom flanges of the beams. Two stressing strands were located on 2-inch centers in the top flanges of the beams, 2 inches down from the top surfaces of the beams: the final two strands were located on 2-inch centers in the web, 8 inches from the top surfaces of the beams. All prestressing steel strands were straight as opposed to deflected or draped strand pretensioning reinforcement.

As indicated by concrete test cylinders cured by methods identical with the curing of the test beams, the compressive strength of the concrete in the 25 bridge beams was 4000 psi when the pretensioning stress was transferred from the steel strands to the concrete of the beams. Designed for a 28-day compressive strength of 5000 psi, the prestressed concrete beams had an average compressive strength of 5,340 psi when tested with the Schmidt concrete test hammer 67 days after release of the prestressing force.

b. **Description of Type-II, Post-Tensioned, Prestressed Beams.** Twenty, AASHO-type-II, standard, prestressed, concrete I-beams post-tensioned with three, parallel,

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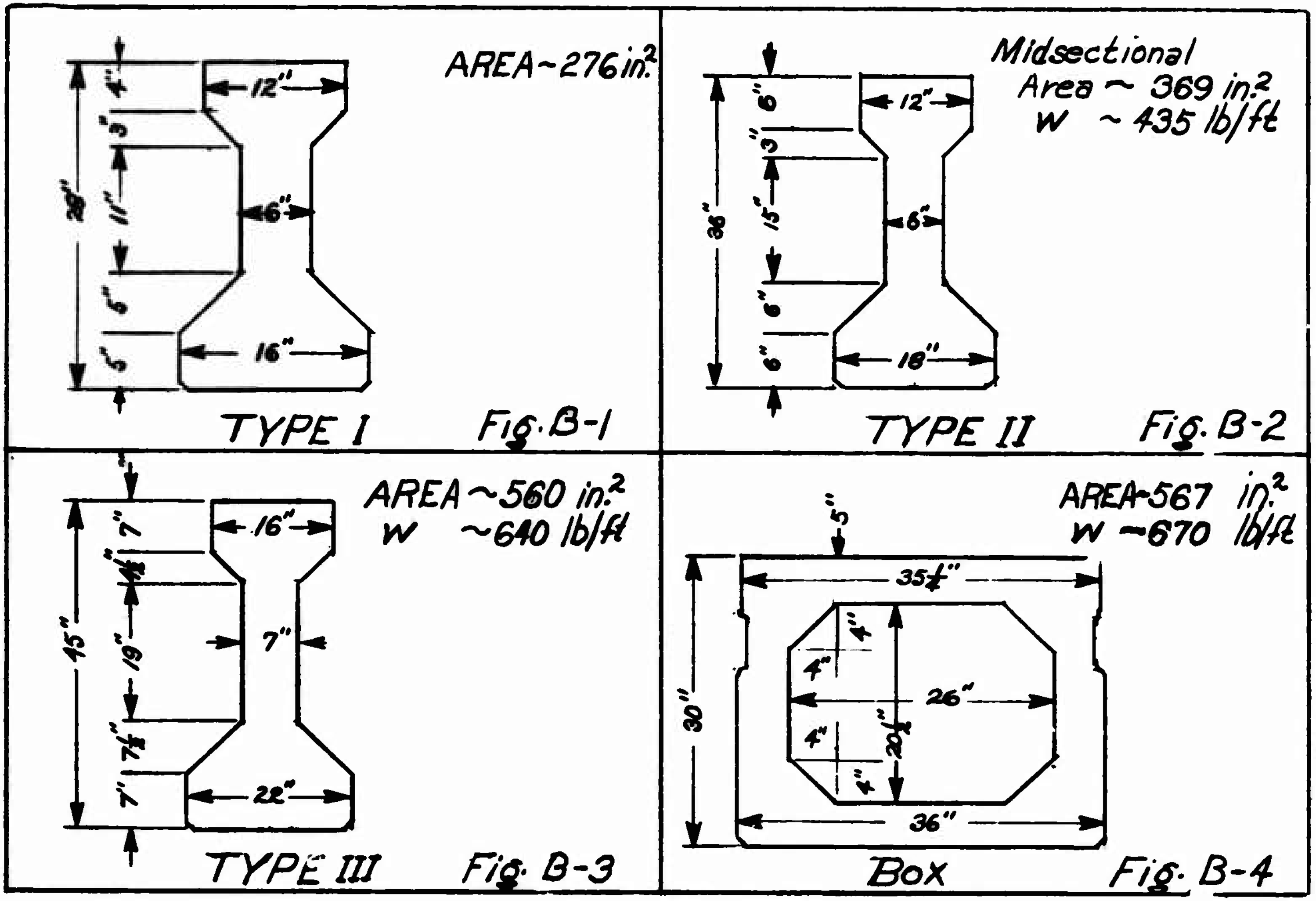
[9] ***Standard Plans for Highway Bridges*** **from** ***Tentative Standards for Prestressed Concrete Piles, Slabs, I-Beams, and Box Beams; Standard Specifications for Highway Bridges,*** **Eighth Edition, AASHO, 1961, pp 126-134.**



AASHO Standard Beam Geometry

1-inch diameter stressteel alloy bars served as simple span bridge beams for explosive demolition experimentation. Constructed of 5000-psi compressive strength concrete, in accordance with AASHO standard specifications for 40- to 60-foot bridge spans of 28-foot-wide roadways, the 30-foot-long I beams weighed 435 pounds per linear foot, or 6½ tons per beam. Specific design characteristics of the beams are illustrated in Fig. B-2.

The AASHO, standard, type-II I beams consisted of post-tensioned, prestressed concrete in which the stressteel alloy bars were tensioned hydraulically after the concrete beams had developed the 4000-psi compressive strength specified to receive the transferred, post-tensioning, prestressing force. The beams were post-tensioned with three, 1-inch-diameter stressteel alloy bars sheathed in flexible metal tubing and located on 2½-inch centers within the bottom flanges of the beams; the metal tubing was pressure grouted after post-tensioning of the beams. The two outside stressteel bars were straight and parallel to each other, but the center stressteel bar was draped so that the ends of the bar were 17 inches above the bottom of the beams with the rod draping downward to where its center was alined parallel with the two outside stressteel bars. Each type-II, post-tensioned, prestressed, concrete beam of 3-foot overall depth had a cross-sectional area of 369 square inches, consisting of a 12-inch-wide by 9-inch-deep top flange, a 15-inch-deep by 6-inch-thick web, and an 18-inch-wide by 12-inch-deep bottom flange. The beams had a 2 foot 10-inch long end blocks of solid, heavily reinforced concrete. Two ½-inch-diameter steel reinforcing bars were embedded in the concrete along the top flange of the 30-foot beams.

c. **Description of Type-III Prestressed Beams.** Twenty, type-III, AASHO-standard, prestressed concrete I-beams were used as the test structures for completion of the explosive demolition experiments begun on this type of bridge beam in 1964. The type-III beams, like the type-I members used in the 1964 tests, were constructed of 28-day, 5,000-psi, compressive-strength concrete in accordance with AASHO standard specifications for 35- to 55-foot bridge spans with 24-foot roadways. Precast at a Winchester, Virginia, prestressed concrete plant during 10 through 13 August 1965, using steel forms and steam curing, the test beams were transported to the test site by trucks on 17 August 1965. These beams were one of four types of composite I-beam cross sections standardized by the Joint Committee of the American Association of State Highway Officials and the Prestressed Concrete Institute for use in construction of prestressed concrete highway bridges in the United States.

The type-III, AASHO-standard I-beams consisted of pretensioned, bonded, prestressed concrete in which the steel stressing strands were tensioned by hydraulic jacks prior to placing the concrete and were released after the concrete had developed the 4,000-psi compressive strength specified to retain the transferred prestressing force through the bond of the concrete to the steel strands. Each type-III prestressed concrete

beam of 45-inch overall depth had a cross-sectional area of 560 square inches, consisting of a 16-inch-wide by 11½-inch-deep top flange, a 19-inch-deep by 7-inch-thick web, and a 22-inch-wide by 14½-inch-deep bottom flange (Fig. B-3). Twenty-four, 7/16-inch-diameter steel strands of 250,000 psi ultimate strength prestressed the concrete beams. The steel stressing strands were pretensioned with an initial tensioning force of 18,900 pounds per strand. Eighteen of the steel stressing strands of the seven-wire type having a center wire enclosed tightly by six helically placed outer wires were located on 2-inch centers in two rows in the bottom flanges of the beams; the first row of 10 strands was 2 inches in from the bottom surface of the tension flange, and the second row of eight strands was located 2 inches above the first row. The other six stressing strands were centered in the web at 2-inch intervals just above the neutral axis of each beam. All prestressing strands were straight as opposed to deflected or draped strand pretensioning reinforcement. Two, ½-inch-diameter steel reinforcing bars were also embedded in the concrete along the top flange of the 30-foot beams which weighed 640 pounds per linear foot, or 9.6 tons per beam.

d. **Description of Prestressed Concrete Box Beams.** Eighteen, AASHO-standard, prestressed concrete box beams served as simple span bridge beams for the demolition experiments. The box beams were constructed of 5,000-psi, compressive-strength concrete in accordance with AASHO standard specifications for 40- to 70-foot bridge spans with 28-foot-wide roadways. These prestressed concrete box beams, which were precast using steel forms and steam curing, were one of four types of box-beam sections standardized by the Joint Committee of the American Association of State Highway Officials and the Prestressed Concrete Institute for use in highway bridges in the United States. The 30-foot-long box beams used in this test program weighed 670 pounds per linear foot, or 10.05 tons per beam.

Each prestressed concrete box beam of 2½-foot depth and 3-foot width had a 567 square inch, cross-sectional area which consisted of a 6-inch-thick top, 5-inch-thick sides, and a 4½-inch-thick bottom (Fig B-4). Nineteen steel strands of 250,000-psi ultimate strength, 7/16 inch in diameter, prestressed the concrete box beams. Thirteen of the steel stressing strands of the seven-wire type (a center wire enclosed tightly by six helically placed outer wires) were located on 2- to 4-inch centers in a single row within the bottom of the beams 2 inches in from its outer surface. The other six steel stressing strands were located on 4-inch centers, three strands each embedded 2 inches within the two sides near the bottom of the box beams. The box beams were constructed of pretensioned, bonded, prestressed concrete in which the steel stressing strands were pretensioned by hydraulic jacks with a tensioning force of 18,900 pounds per strand prior to placing the concrete. Tensioned strands were released after the concrete had developed the 4,000-psi compressive strength specified to retain the transferred prestressing force through the bond of the concrete to the steel strands. Four steel reinforcing bars, 1/2 inch in diameter, strengthened by lateral reinforcing steel, were also embedded in the

concrete along the top of the 30-foot beams. There was 2 feet of solid concrete at each end of the box beams which had 12-2/3-foot-long octagonal voids which separated 2/3 foot of solid concrete at the beam center.

On bridge substructure supports, precast, prestressed concrete box beams are laid adjacent to each other, and the intervening longitudinal joints are mortared to form the stringers and floor slab of box-beam bridges which are now used almost as extensively in prestressed concrete bridge construction as in the composite I-beam bridge. Eleven adjoining box beams form a 28-foot-wide roadway of a prestressed, box-beam bridge span. Transverse tie rods of steel, 1-5/8 inches in diameter, are used at the diaphragms for lateral tensioning, and a bituminous wearing surface is placed over the tops of the adjoining box beams. Prestressed concrete box beams have circular voids for short spans and rectangular or octagonal voids for medium spans. Some details of prestressed concrete box beam bridges are given in Figs. B-5, B-6, and B-7. Figures B-8 and B-9 show the optimum placement areas for maximum demolition effect for box-beam structures.

e. **Prestressed Concrete Beam Test Geometry.** Figure B-10 shows the test configurations used in the experimental programs. All test elements when initially placed on the abutments were 30 feet overall in length with a 28-foot clear span. Only the type-I (AASHO) beam utilized weights (5000 pounds each) at each of the piers as shown in B-10 (a).

A test was considered a success when its final configuration approximated that shown in B-10 (b) or was both off the piers and severed. Tests were conducted on elements of the beam which were on the ground and on beams which were still remaining on the piers after an initial charge failed to sever the beam completely (exclusive of steel elements).

B-10 (a) shows the "ideal" break in which a minimum amount of concrete is removed in the form of a wedge at the midpoint of the beam which constitutes the most critical area of a simply supported beam in flexure. B-10 (b) shows that removal of a 2-foot sectional slice would reflect the maximum amount of concrete that should be removed if the beam were to fall between the piers.

Table B-2 shows the geometric area and volume relationship for the four, AASHO-type beams which were tested and analyzed for this study.

f. **Test Beam Charge Calculations.** Tables B-3 through B-9 inclusive were calculated for three standard explosives (C-4, TNT, Detasheet-C) for the four prestressed beam types employing formulae from FM 5-25 and ERDL Report 1663-TR as applicable.[10]

[10]Howard J. Vandersluis, *Hasty Demolition of Concrete Structures*, Technical Report 1663-TR, USAERDL, Fort Belvoir, Virginia, January 1961.

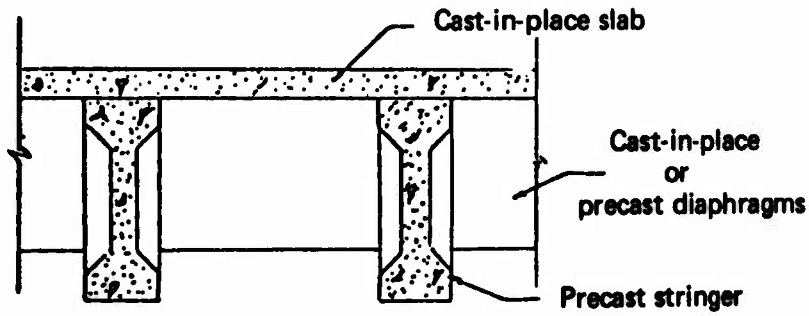
Type: Composition I-beam

Construction: Precast stringers with cast-in-place slab

Slab thickness: 6" to 8"

Wearing surface: Optional

	Posttensioned	Pretensioned
Min. span	40'	30'
Usual depth/span ratio	1/12	1/11
Max. span	140'	100'
Usual depth/span ratio	1/18	1/15
Beam spacing	5'–0" to 8'–0"	5'–0" to 8'–0"
Prestressing steel	Bars, wire cable	Small-diam. strand



Details of composite I-beam prestressed concrete bridge (most predominant in the United States).

Fig. B-5. Composition I-Beam.

Type: Box beam slab

Construction: Precast pretensioned sections placed adjacent to each other and longitudinal joints dry packed. Occasionally posttensioned.

Slab thickness: 4" to 5"

Wearing surface: 2" to 4" bituminous

Min. span: 20'
Usual depth/span ratio: 1/14

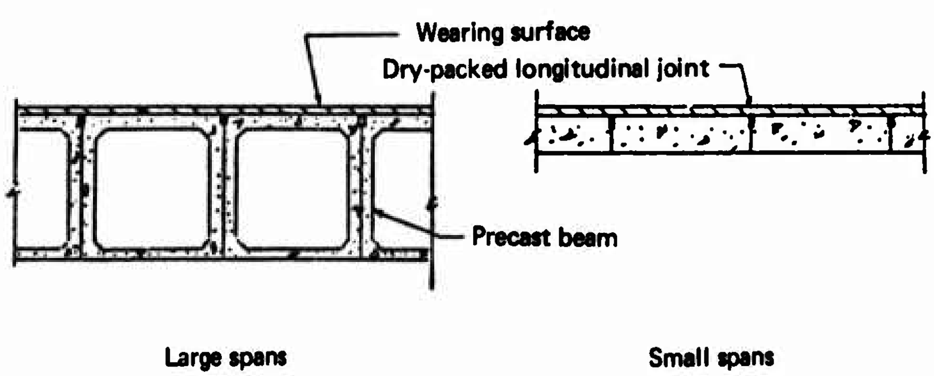
Max. span: 110'
Usual depth/span ratio: 1/26

Beam spacing: 3'–0" to 4'–0"

Prestressing steel

Pretensioned: Small-diam. strand
Posttensioned: Wire cable, bars

Transverse tie rods used at diaphragms.



Details of prestressed concrete box beam slab bridge (second most predominant in the United States).

Fig. B-6. Box Beam Slab.

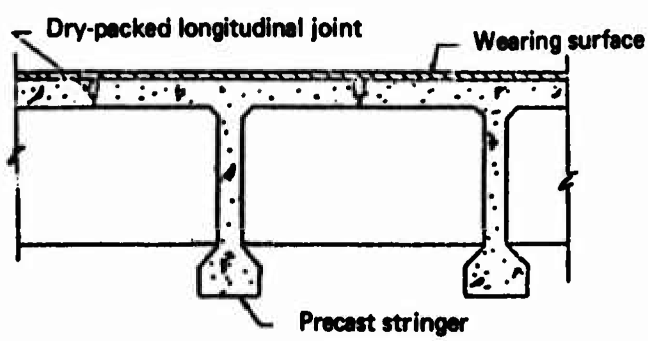
Type: T-beams

Construction: Precast T-beams placed adjacent to each other and longitudinal joints dry packed.

Slab thickness: 6" to 8"

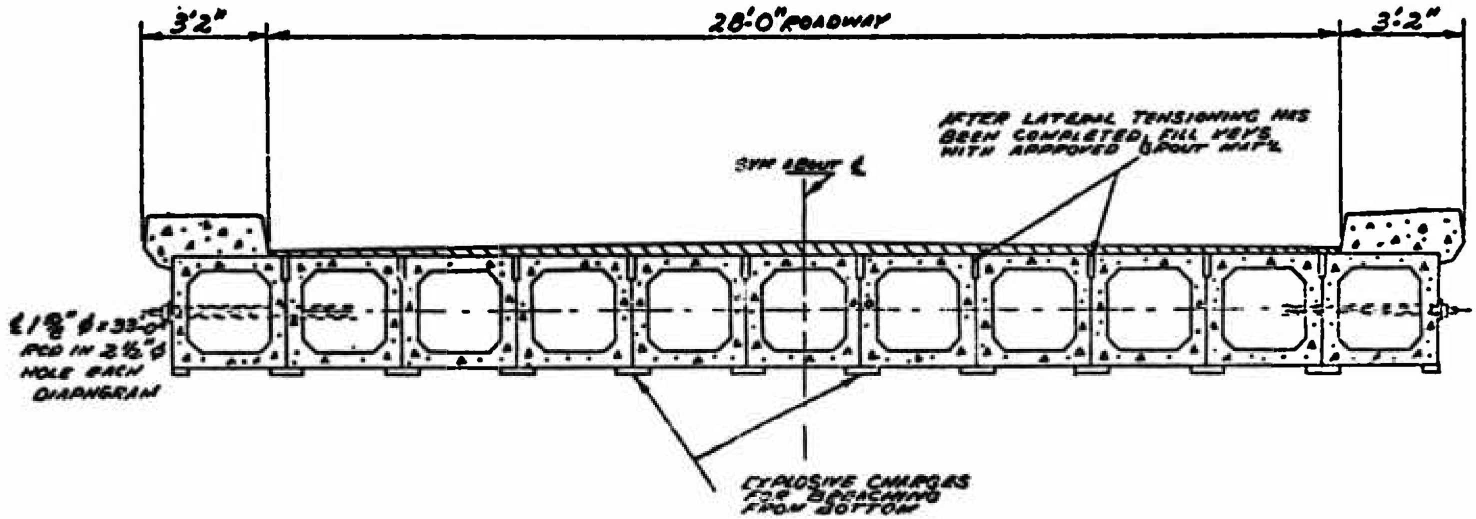
Wearing surface: 2" to 4" bituminous

	Posttensioned	Pretensioned
Min. span	40'	30'
Usual depth/span ratio	1/20	1/18
Max. span	170'	80'
Usual depth/span ratio	1/24	1/21
Beam spacing	3'–0" to 6'–0"	2'–0" to 5'–0"
Prestressing steel	Bars, wire cable, large-diam. strand	Small-diam. strand



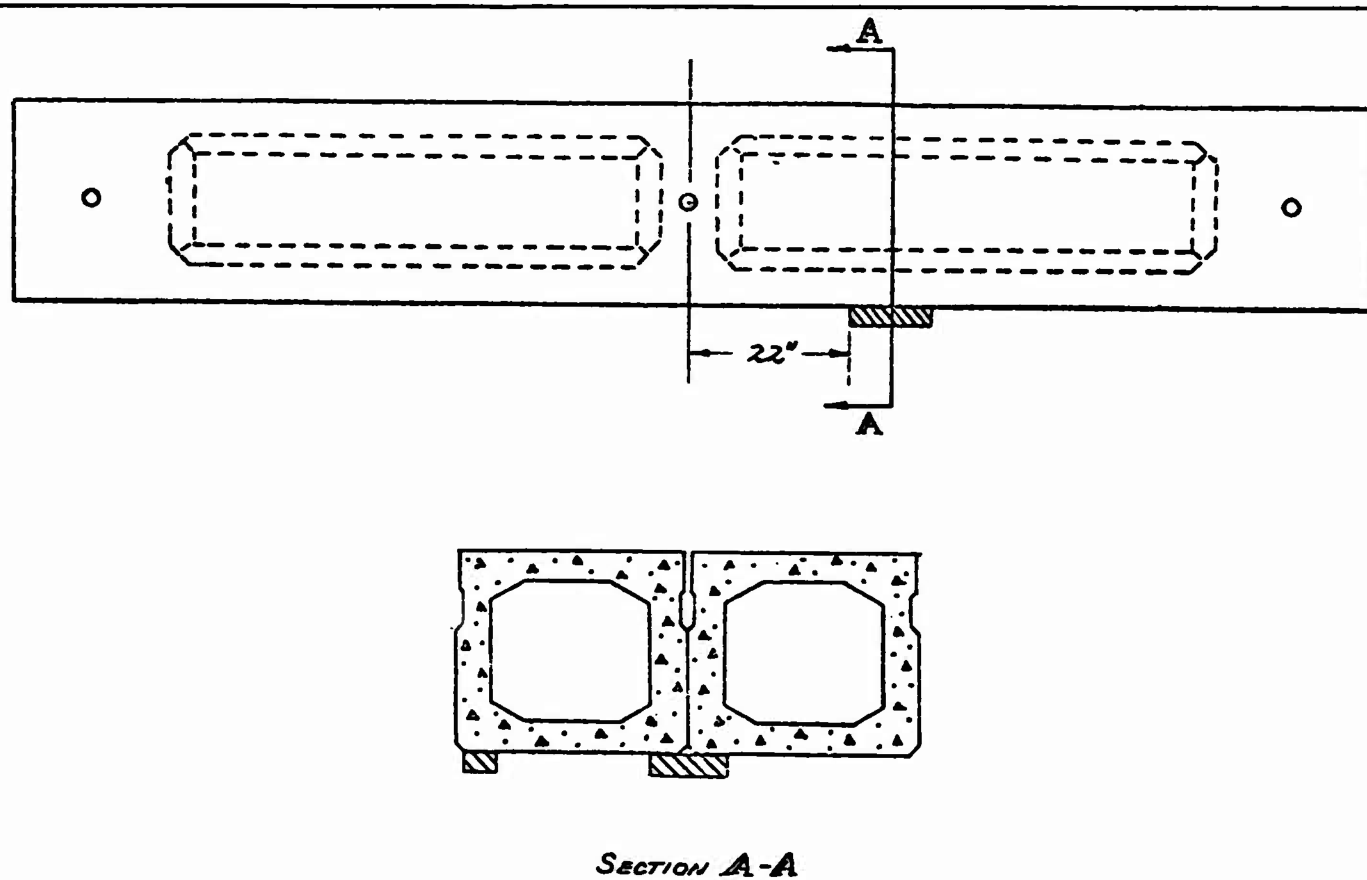
Details of prestressed concrete T-beam bridge (most predominant in Western Europe).

Fig. B-7. T-Beams.



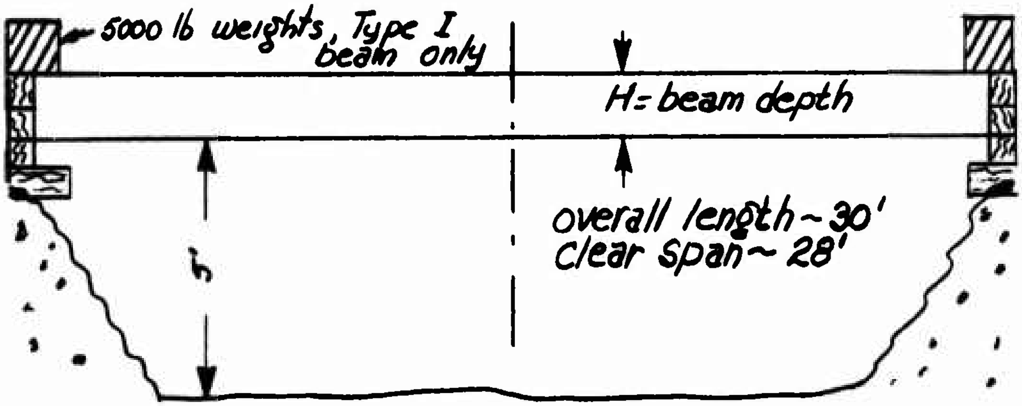
Charge placements for explosive demolition of prestressed concrete bridge spans of box beam construction. (Figure portrays charge placements for a 28-foot-wide bridge span of 11 adjacent, prestressed, concrete box beams. Charge placements would be similar for demolition of beams from the top surface roadway.)

Fig. B-8. Box Beam Bridge Charge Placement.



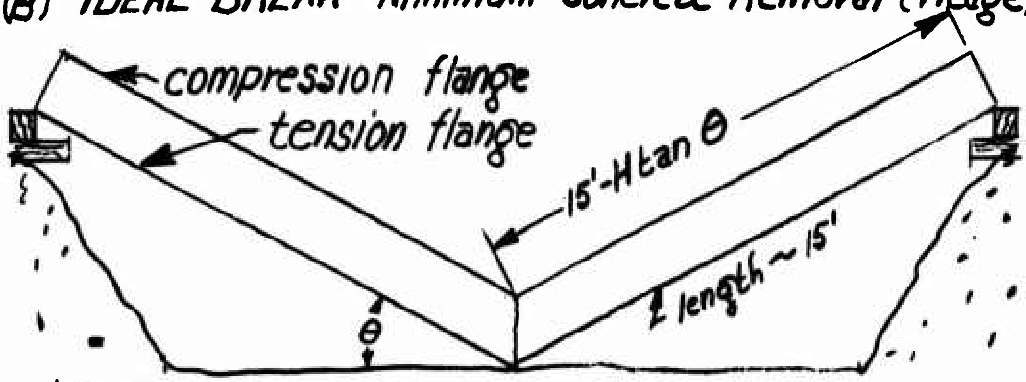
Placement of explosive charges for demolition of prestressed concrete box beams (charges are offset 22 inches from solid concrete center and diaphragm rod of beam at Section A-A) (charge placement would be similar for demolition from top surface with pressure charges).

Fig. B-9. Box Beam Charge Placement.



(A) TEST CONFIGURATION ~ Simply Supported Beam

(B) IDEAL BREAK ~ Minimum Concrete Removal (Wedge)



$\tan\theta \approx 5/14 = 0.356$

Beam Type	H in.	H feet	$H\tan\theta$ feet	Top flange loss feet	Top flange loss Inches
I	28	2.33	0.827	1.654	19.85
II	36	3.00	1.065	2.130	25.56
III	45	3.67	1.303	2.606	31.27
Box	30	2.50	0.888	1.776	21.31

(C) BEAM BREAK ~ Maximum Concrete Removal
Make tension flange length = Compression flange length = 2 feet, permitting the severed beam segments to rotate vertically and fall free of the piers or abutments

Fig. B-10. Concrete Beam Test Geometry.

Table B-2. Concrete Beam Relationships (Geometry/Area/Volumes)

Beam Type (AASHO)	Depth of Beam (in.)	Cross-Section Area (in.)^2	Flange Width Top (in.)	Flange Width Bot. (in.)	Concrete Material Removal: 24-Inch Slide Section Area* (in.^{2})	Area Ratio				Volume (in.)^3	Volume Ratio				Wedge Section Area* (in.)^2	Area Ratio				Volume (in.)^3	Volume Ratio			
I	28	276	12	16	552	1.00	0.75	0.49	0.49	6624	1.00	0.75	0.49	0.99	591	1.00	0.75	0.49	0.49	2253	1.00	0.54	0.29	0.37
II	36	369	12	18	738	1.33	1.00	0.66	0.65	8856	1.33	1.00	0.66	0.65	790	1.34	1.00	0.66	0.65	4159	1.85	1.00	0.54	0.69
III	45	560	16	22	1120	2.03	1.52	1.00	0.99	13,440	2.03	1.52	1.00	0.99	1198	2.02	1.51	1.00	0.99	7746	3.43	1.86	1.00	1.28
Box	30	567	17¾	18	1134	2.06	1.54	1.01	1.00	13,608	2.06	1.54	1.01	1.00	1213	2.04	1.54	1.01	1.00	6015	2.67	1.45	0.78	1.00

*Area is the cross-sectional area exposed in the beam after the material is removed.

(Length of cut along top flange (compression flange) for the wedge section

I – 19.85 in., II – 25.56 in., III – 31.27 in., Box – 21.31 in.)

Table B-3 contains the explosive charge requirements as determined from the data presented in ERDL Report 1663-TR. This report pointed out the effect of the thickness to area ratio of the explosive charge and related this value to charge weight which in turn was correlated to thickness of concrete in a wall to be breached. The concrete in the wall was defined as an excellent product. The experimental values were determined for composition C-4 explosive. The effectiveness factors of 1.00 (TNT), 1.34 (C-4), and 1.14 (Detasheet-C) were used to complete the tables. It should be pointed out that this report did not consider any form of prestressed concrete in the experimental program.

Table B-3. Reinforced Concrete Demolition Breaching Calculations
(Data based on ERDL Tech Rpt 1663-TR)

Prestressed Beam Type (AASHO)	Beam Depth (in.) (ft)	Thickness to Area Ratio of Explosive Charge	Explosive Charge Requirements (weight in pounds)		
			C-4	Detasheet	TNT
I	28, 2.33	1:68	11.0	13.0	14.7
II	36, 3.00	1:80	15.0	17.6	20.1
III	45, 3.67	1:100	29.0	34.0	38.8
Box	30, 2.50	1:70	11.9	14.0	15.8

Note: Charge placement on top surface of beam (compression flange top surface).

Effectiveness Factors (from FM 5-25)	
TNT	1.00
C-4	1.34
Detasheet C	1.14

Table B-4 was calculated for the 4 beam types and 3 explosives using the pressure calculation formulae for tamped and untamped charges placed on the top surface of the beam. The calculations for beam Types I, II, and III included three values for beam thickness in the pressure formulae. They were the two flange widths plus the average thickness, which is defined as the cross-sectional area divided by the beam height (A/H = T). The three values of thickness were used for correlation/comparison to the experimental data in order to determine the most representative thickness for application to the pressure-calculation formulae.

Table B-5 contains breaching calculations for the 4 beam types, 3 explosives, 3 tamping factors, and the material factor; all calculations were performed in accordance with the latest FM 5-25. It should be pointed out that while the tables reflect no difference in results when the charge is placed on the bottom face of the tension flange or when the charge is placed on the top face of the compression flange, the charge should be more effective at the bottom flange because of the placement of the prestressing steel

Table B-4. Reinforced Concrete Demolition (Pressure calculations based on FM 5-25)

($P = 3H^2 T$ or $4H^2 T$)

Prestressed Beam Type (AASHO)	H Depth of Beam (feet)	H^2 (feet^2)	A Beam Cross-Section Area (in.^{2})	Average Thickness (A/H) (in.)	Explosive Charge (lb) 3H²W (Tamped) C-4	3H²W (Tamped) DS-C	3H²W (Tamped) TNT	4H²W (Untamped) C-4	4H²W (Untamped) DS-C	4H²W (Untamped) TNT
I	2.33	5.43	276	9.9	10.0	11.8	13.4	13.4	15.7	17.9
				(12" flange)	12.2	14.3	16.2	16.2	19.0	21.7
				(16" flange)	16.2	19.1	21.6	21.6	25.4	28.9
II	3.00	9.00	369	10.25	17.3	20.3	23.1	23.0	27.1	30.8
				(12" flange)	20.3	23.8	27.0	26.9	31.7	36.1
				(18" flange)	30.4	35.6	40.6	40.4	47.6	54.1
III	3.67	13.47	560	12.45	30.6	35.9	40.9	40.8	47.8	54.5
				(16" flange)	39.3	46.1	52.6	52.4	61.4	70.0
				(22" flange)	54.1	63.4	72.3	72.1	84.6	96.3
Box	2.50	6.25	567	18.90	22.1	26.0	29.6	29.6	34.8	39.6

Note: Charge placement on top surface of beam (compression flange).
(DS-C = Detasheet C explosive)

Table B-5. Reinforced Concrete Demolition (Breaching calculations based on FM 5-25)

$(P = R^3CK)$

Prestressed Beam Type (AASHO)	R Thickness of Beam (feet)	R^3 (feet³)	K Material Factor	Explosive Charge Requirements (lb) C = Tamping Factor = 1.8 C-4	DS-C	TNT	C = 2.0 C-4	DS-C	TNT	C = 3.6 C-4	DS-C	TNT
I	2.33	12.65	0.96	16.4	19.2	21.9	18.2	21.3	24.3	32.6	38.3	43.7
	(2.5)	(15.625)	(0.96)	(20.2)	(23.7)	(27.0)	(22.4)	(26.3)	(30.0)	(40.3)	(47.4)	(54.0)
II	3.00	27.00	0.80	29.1	34.1	38.9	32.3	37.9	43.2	58.1	68.3	77.8
III	3.67	49.43	0.80	53.2	62.5	71.2	59.1	69.4	79.1	106.3	124.9	14
	(4.0)	(64.00)	(0.80)	(68.8)	(81.2)	(92.2)	(76.5)	(89.8)	(102.4)	(137.6)	(161.8)	(184.4)
Box	2.50	15.625	0.96	20.2	23.7	27.0	22.4	26.4	30.0	40.3	47.4	54.0

Note: Charge placement is on bottom or top of beam (on face of either tension or compression flange).
DS-C = Detasheet-C.
Values in parentheses in accordance with FM 5-25 (round off measurements to next higher 0.5 increment).

Table B-6. Reinforced Concrete Demolition (Breaching calculations based on FM 5-25) Web

($P = R^3 CK$)

Prestressed Beam Type (AASHO)	R Critical Radius from Midpoint of Web (feet)	R^3 (feet^3)	K Material Factor	Explosive Charge Requirements (lb) C = Tamping Factor = 1.8 C-4	DS-C	TNT	C = 2.0 C-4	DS-C	TNT	C = 3.6 C-4	DS-C	TNT
I	1.5	3.375	0.96	4.4	5.2	5.9	4.9	5.7	6.5	8.7	10.3	11.7
II	1.6	4.10	0.96	5.3	6.2	7.1	5.9	6.9	7.9	10.6	12.5	14.2
	(2.0)	(8.00)	(0.96)	(10.4)	(12.2)	(13.9)	(11.5)	(13.5)	(15.4)	(20.7)	(24.3)	(27.7)
III	2.2	10.65	0.96	13.8	16.2	18.5	15.3	13.5	20.5	27.5	24.3	36.9
	(2.5)	(15.625)	(0.96)	(20.2)	(23.7)	(27.0)	(22.4)	(26.3)	(30.0)	(40.3)	(47.4)	(54.0)
Box	1.95	7.41	0.96	9.6	11.3	12.9	10.7	12.5	14.3	19.2	22.5	25.7
	(2.0)	(8.00)	(0.96)	(10.6)	(12.4)	(14.2)	(11.8)	(13.8)	(15.8)	(21.2)	(25.0)	(28.4)

Note: Charge placement is at midpoint axis of the beam web (it is a side-breaching charge).
(DS-C = Detasheet-C)
Values in parentheses in accordance with FM 5-25 (round off measurements to the next higher 0.5 increments for the dimensions in feet).

Table B-7. Reinforced Concrete Demolition
(Breaching Calculations, Type I, AASHO Prestressed Beam)

Area of Explosive Effort	R Critical Radius (in.)	R^3 $(in.)^3$	K Material Factor	Explosive Charge Requirements (lb) C = Tamping Factor = 1.8 C-4	DS-C	TNT	C = 2.0 C-4	DS-C	TNT	C = 3.6 C-4	DS-C	TNT
Compression Flange Steel												
From top	2.9	24.389	1.76	.0335	.0393	.0449	.0372	.0437	.0498	.0670	.0787	.0898
Under face	6.6	287.496	1.76	.394	.464	.529	.439	.525	.588	.788	.928	1.058
Both under faces	5.0	125.000	1.76	.1710	.201	.2294	.190	.223	.2548	.342	.403	.4587
Web Steel	4.0	64.00	1.76	.0877	.1028	.1176	.0972	.1142	.1306	.175	.206	.2351
Tension Flange Steel												
Top face	12.8	2097.15	1.76	2.89	3.39	3.87	3.20	3.76	4.29	5.76	6.77	7.73
Both top faces	7.8	474.552	1.76	.657	.765	.871	.723	.847	.968	1.31	1.528	1.742
Underside of flange	7.25	381.078	1.76	.523	.614	.701	.580	.681	.778	1.045	1.228	1.401

Table B-8. Reinforced Concrete Demolition
(Breaching Calculations, Type II, AASHO Prestressed Beam)

Area of Explosive Effort	R Critical Radius (in.)	R^3 (in.^{3})	K Material Factor	Explosive Charge Requirements (lb)								
				C=Tamping Factor = 1.8			C = 2.0			C = 3.6		
				C-4	DS-C	TNT	C-4	DS-C	TNT	C-4	DS-C	TNT
Compression Flange												
Steel												
From top	3.5	42.875	1.76	.0585	.0690	.0786	.0650	.0765	.0873	.1170	.1380	.1572
Under face	7.2	373.25	1.76	.510	.601	.685	.566	.667	.760	1.020	1.200	1.369
Both under faces	6.0	216.00	1.76	.296	.348	.396	.328	.386	.440	.590	.695	.792
Web (no steel) (thickness at web)	6.0	216.00	1.76	.296	.348	.396	.328	.386	.440	.590	.695	.792
Tension Flange												
Steel												
Top face	8.1	531.44	1.76	.728	.855	.976	.808	.951	1.084	1.454	1.710	1.952
Both top faces	7.6	438.98	1.76	.600	.706	.805	.666	.784	.894	1.200	1.410	1.609
Under side of flange	5.2	140.61	1.76	.192	.226	.2579	.213	.250	.2865	.384	.452	.5157

Table B-9. Reinforced Concrete Demolition
(Breaching Calculations, Type III, AASHO Prestressed Beam)

Area of Explosive Effort	R Critical Radius (in.)	R^3 (in.^{3})	K Material Factor	Explosive Charge Requirements (lb) C=Tamping Factor = 1.8 C-4	DS-C	TNT	C = 2.0 C-4	DS-C	TNT	C = 3.6 C-4	DS-C	TNT
Compression Flange												
Steel												
From top	2.5	15.625	1.76	.0214	.0252	.0287	.0238	.0279	.0319	.0427	.0502	.0573
Under face	9.3	804.36	1.76	1.100	1.295	1.476	1.222	1.440	1.640	2.200	2.590	2.953
Both under faces	8.4	592.70	1.76	0.810	0.954	1.087	0.902	1.059	1.207	1.620	1.910	2.174
Web steel	5.0	125.00	1.76	.1710	.201	.2294	.190	.223	.2548	.342	.403	.4586
Tension Flange												
Steel												
Top face	18.5	6331.6	0.96	4.73	5.57	6.35	5.26	6.17	7.05	9.45	11.11	12.68
Both top faces	11.4	1481.5	1.76	2.03	2.38	2.72	2.25	2.65	3.02	4.05	4.77	5.437
Underside of flange	9.3	804.36	1.76	1.100	1.295	1.476	1.222	1.440	1.640	2.200	2.590	2.953

and the reversal of load direction in the beam. Data in the table show the effect of "rounding-off" dimensions for use in the formulae. For large values of R, the variance approaches +50%; for small values, it approaches +25%.

Table B-6 contains side-breaching calculations for the 4 beam types, 3 explosives, 3 tamping factors, and material factor. The side-breaching calculations were performed using a single charge centered at the midpoint of the web of the beam (the beam web is the vertical portion of the beam between the top and bottom flanges). The "rounding-off" effect for the beam measurement approaches +100% in one calculation in this table.

Table B-7 contains breaching calculations for the type-I beam, 3 tamping factors, and the material factor. The critical radii used in developing these data were determined graphically from the drawing for the beam. Criterion used for each of the respective radii was that the measurement be taken to the point of placement of the steel from the closest surface of the beam. The steel located in the compression flange, web, and tension flange determined the target areas. The calculations show several possible charge combinations requiring a minimum placement of three to a maximum placement of five different charges in order to perform demolition of the beam. It should be pointed out that it may not be possible in an operational environment to position the calculated charges on the beam as required nor would military personnel have access to a drawing showing the amount and placement of the prestressing steel. The data do define a minimum demolition weight for the respective beam types and should prove useful in that respect.

Tables B-8 and B-9 contain similar calculations for the type-II and type-III prestressed concrete beams. The box beam does not lend itself to such analyses.

The following sections contain the compilations for the experimental data and analysis for AASHO-Type prestressed concrete beams:

Experimental Results: Type I, AASHO Beam[11]

Experimental Charge	No. of Tests	No. of Effective Cuts	Most Effective Charge (lb)	Average Time to Emplace, Fasten, and Prime a Prepared Charge
Pressure, tamped	12	9	17	5 minutes
Pressure, untamped	12	7	26.4	< 5
Bottom breaching	16	11	15	10
Dual side breaching	39	30	1.9	20
Shaped Charge				
DM 29	4	0	8.8	(Two charges emplaced)
DM 19	14	14	19.8	($\frac{TNT}{RDX} = \frac{49}{51}$ Ratio)
USAERDL A	2	0	5.0	(C-4)
B	2	0	7.8	(C-4)
C	4	4	9.5 – 9.6	(C-4)

Pressure-tamped formula

$K_{explosive} = 1.34$ (C-4)

$W = (\frac{12+16}{2}) = 14$ inch

$H = 28, H^2 = 784$

$P_{exp} = 17$ lb (tamped)

$$P_{exp} = K_{exp} \frac{H^2 W}{K_{explosive}}$$

$$\text{then } K_{exp} = \frac{1.34\, P_{exp}}{14 \times 784}$$

$$K_{exp} = \frac{1.34 \times 17 \text{ lb}}{10976 \text{ in.}^3} = 0.00207 \frac{\text{lb}}{\text{in.}^3}$$

$$\boxed{\begin{aligned} P &= 0.00207\, H^2 W \text{ (TNT)} \\ P &= 0.00155\, H^2 W \text{ (C-4)} \\ P &= 0.00182\, H^2 W \text{ (DS-C)} \end{aligned}}$$

Pressure-untamped formula

$P_{exp} = 26.4$ lb

$$K_{exp} = \frac{1.34 \times 26.4}{14 \times 784} = 0.00322$$

$$\boxed{\begin{aligned} P &= 0.00322\, H^2 W \text{ (TNT)} \\ P &= 0.00241\, H^2 W \text{ (C-4)} \\ P &= 0.00283\, H^2 W \text{ (DS-C)} \end{aligned}}$$

[11] James A. Dennis, *Demolition of Prestressed Concrete Bridge Beams with Explosive (Phase I)*, Report 1830, USAERDL, Fort Belvoir, Virginia, September 1965.

Type I (cont'd)

Bottom-breaching formula

P_{exp} = 15 lb

R = 28, R^3 = 21,952

K = 0.96 (Table 3-2, FM 5-25)

$K_{explosive}$ = 1.34

$$P_{exp} = \frac{5.79 \times 10^{-4}\ R^3\ KC}{K_{explosive}}$$

$$15 = \frac{5.79 \times 10^{-4} \times 21{,}952 \times 0.96\ C}{1.34}$$

$$15 = \frac{5.79 \times 2.1074\ C}{1.34}$$

C = 1.6 for charge placed on bottom face of beam

Top-breaching formula

P_{exp} = 26.4 lb (from value for untamped pressure charge)

R = 28, R^3 = 21,952

K = 0.96

$K_{explosive}$ = 1.34

$$26.4 = \frac{5.79 \times 10^{-4} \times 21{,}952 \times 0.96\ C}{1.34}$$

$$26.4 = \frac{5.79 \times 2.1074\ C}{1.34}$$

C = 2.9 for charge placed on top of beam

Dual-side-breaching formula

R_T = top flange radius = 6.6 inch

R_B = bottom flange radius = 12.8 inch

K_T = material factor at the top flange = 1.76

K_B = material factor at the bottom flange = 1.76

$\left(\frac{C_T + C_B}{2}\right)$ = average tamping factor

P_{exp} = 1.9 lb

$K_{explosive}$ = 1.34

$$P_{exp} = \frac{5.79 \times 10^{-4} (R_T^3 + R_B^3) \left(\frac{K_T + K_B}{2}\right) \left(\frac{C_T + C_B}{2}\right)}{K_{explosive}}$$

$$1.9 = \frac{5.79 \times 10^{-4} \times 2385 \times 1.76\ (C_T + C_B)}{1.34 \times 2}$$

$(C_T + C_B)$ = 2.1 for dual breaching charges placed on sloping faces of top and bottom flanges

$$\text{Charge weight proportions} = \left(\frac{6.6}{12.8}\right)^3 = \frac{1}{7.3} = \frac{0.229 \text{ lb}}{1.670 \text{ lb}}$$

Type I (cont'd)

Linear-shaped charge, USAERDL IMC-C (on tension flange)

$P_{exp} = 9.5 - 9.6$ lb

$K_{explosive} = 1.34$

Compare with bottom-breaching formulae results for C = 1.6

$$\text{then } \frac{9.6}{15} = \frac{C}{1.6}$$

$$C = \frac{9.6 \times 1.6}{15} = 1.04$$

Extrapolated linear-shaped charge (on compression flange)

Breaching

$C_{bottom} = 1.6$

$C_{top} = 2.9$

$K_{explosive} = 1.34$

Shaped

$C_{bottom} = 1.04$

$$C_{top} = \frac{2.9 \times 1.04}{1.6} = 1.88$$

Predicted C-4 shaped charge weight for application to top face of the beam (compression flange)

$$P = \frac{5.79 \times 10^{-4}\ R^3 KC}{K_{explosive}}$$

$$P = \frac{5.79 \times 10^{-4} \times 21{,}952 \times 0.96 \times 1.88}{1.34}$$

$$\boxed{P = 17\text{-lb shaped charge}}$$

Experimental Results: Type II, AASHO Beam[12]

Experimental Charge	No. of Tests	No. of Effective Cuts	Most Effective Charge (lb)	
Pressure				
Tamped	6	4	30.25	
Untamped	9	5	56.5	
Bottom breaching	20	2	55	
Dual side breaching	40	36	$\leq$ 5.0	
		34	$\leq$ 3.25	
	(5)	(5)	= 2.65	
	(16)	(13)	= 2.375	← Selected for calculations
Shaped charge				
M2A3	21	20	11½*	(Comp. B or Pentolite)
M3	9	9	30	(Comp. B or Pentolite)

*Effective on both top and bottom flange emplacement.

Pressure-tamped formula

$P_{exp} = 30.25$ lb

$W = 36$ in., $H^2 = 1296$

$T = \left(\frac{12+18}{2}\right) = 15$

$K_{explosive} = 1.34$

$$P_{exp} = \frac{K_{exp}\, H^2 W}{K_{explosive}}$$

$$K_{exp} = \frac{30.25 \times 1.34}{1296 \times 15}$$

$$\boxed{K_{exp} = 0.00208 \text{ lb/in.}^3}$$

Pressure-untamped formula

$P_{exp} = 56.5$ lb

$$P_{exp} = \frac{K_{exp}\, H^2 W}{K_{explosive}}$$

$$K_{exp} = \frac{56.5 \times 1.34}{1296 \times 15}$$

$$\boxed{K_{exp} = 0.00389 \text{ lb/in.}^3}$$

[12] James A. Dennis, *Demolition of Post-Tensioned, Prestressed, Concrete Bridge Beams with High-Explosive Charges (Phase IV-Final Phase)*, Report 1959, USAMERDC, Fort Belvoir, Virginia, July 1969.

Bottom-breaching formula

$R = 36$ inch, $R^3 = 46{,}656$

$P_{exp} = 55$ lb

$K_{explosive} = 1.34$

$K = 0.96$

$$P_{exp} = \frac{5.79 \times 10^{-4}\ R^3KC}{K_{explosive}}$$

$$55 = \frac{5.479 \times 10^{-4} \times 46{,}656 \times 0.96\ C}{1.34}$$

$C^* = 2.6$

*Based on insufficient data (2 out of 10 shots)

Dual-side-breaching formula

$R_T = 7.2$ in., $R_T^3 = 373$

$R_B = 8.1$ in., $R_B^3 = 531$

$K_T = 1.76$

$K_B = 1.76$

$P_{exp} = 2.375$ lb

$K_{explosive} = 1.34$

$\left(\frac{C_T + C_B}{2}\right)$ = average tamping factor

$$P_{exp} = \frac{5.79 \times 10^{-4}(R_T^3 + R_B^3) \times \left(\frac{K_T + K_B}{2}\right) \times \left(\frac{C_T + C_B}{2}\right)}{K_{explosive}}$$

$$2.375 = \frac{5.79 \times 10^{-4}(904)(1.76)(C_T + C_B)}{1.34 \times 2}$$

$C_T + C_B = 6.93$ for dual breaching charges placed on sloping faces of top and bottom flanges

Top-breaching formula

$P_{exp} = 56.5$ lb from pressure, untamped formula

$R = 36$ in., $R^3 = 46{,}656$

$K = 0.96$

$K_{explosive} = 1.34$

$$P_{exp} = \frac{5.79 \times 10^{-4}\ R^3KC}{K_{explosive}}$$

$$56.5 = \frac{5.79 \times 10^{-4} \times 46{,}656 \times 0.96 \times C}{1.34}$$

$C = 2.9$ for breaching charge placed on top of beam

Shaped charge, M2A3

$P_{exp} = 11.5$ lb, other is the same as above

$$\frac{56.5}{11.5} = \frac{2.93}{C}$$

$$\boxed{C = \frac{11.5 \times 2.93}{56.5} = 0.6}$$

Experimental Results: Type III AASHO[13]

Experimental Charge	No. of Tests	No. of Effective Cuts	Most Effective Charge (lb)	
Pressure Tamped	10	1	75	One diamond shape charge of two tried
Bottom breaching	13	3	75	
Dual side breaching	72	51	⩽ 5	All explosives
	(8)	(7)	3.750	C-4 (41 total)
	(8)	(8)	3.250	
	(9)	(9)	3.1875	
	(7)	(4)	3.125	
	(4)	(2)	3.000	
	(1)	(1)	2.875	
	19	8	4.375	Detasheet-C (Flex-X)
	12	8	4.875	TNT

Explosive Effectiveness Factor based on test data

$$\frac{\text{TNT}}{(\text{Flex-X})} = \frac{4.875}{4.375} = 1.11 \qquad \frac{\text{TNT}}{\text{C4}} = \frac{4.875}{3.311} = 1.48$$

Pressure-tamped formula

$P_{exp} = 75$ lb

$H = 45$ in., $H^2 = 2025$

$W = \left(\frac{16+22}{2}\right)$

$K_{explosive} = 1.34$

$$P_{exp} = \frac{K_{exp}\, H^2 W}{K_{explosive}}$$

$$75 = \frac{K_{exp}\, 2025 \times 19}{1.34}$$

$K_{exp}{}^{*} = 0.00262 \text{ lb/in.}^3$

*Based on insufficient data

[13] James A. Dennis, *Demolition of AASHO Standard Type III Prestressed Concrete Beams with High-Explosive Charges (Phase II)*, Report 1853, USAERDL, Fort Belvoir, Virginia, April 1966.

Bottom-breaching formula

$P_{exp} = 75$ lb

$R = 45$ in., $R^3 = 91{,}125$

$K = 0.80$

$K_{explosive} = 1.34$

$$P_{exp} = \frac{5.79 \times 10^{-4}\ R^3 KC}{K_{explosive}}$$

$$75 = \frac{5.79 \times 10^{-4} \times 91{,}125 \times 0.80\ C}{1.34}$$

$C = 2.38$ for charge placed on bottom face of beam

Dual-side-breaching

$R_T = 9.3$, $R_T^3 = 804$

$R_B = 18.5$, $R_B^3 = 6332$

$K_T = 1.76$

$K_B = 0.96$

$P_{exp} = 3.311$ lb

$K_{explosive} = 1.34$

$$P_{exp} = \frac{5.79 \times 10^{-4} (R_T^3 + R_B^3) \left(\frac{K_T + K_B}{2}\right) + \left(\frac{C_T + C_B}{2}\right)}{K_{explosive}}$$

$$3.311 = \frac{5.79 \times 10^{-4} \times 7136 \times 1.36\ (C_T + C_B)}{1.34 \times 2}$$

$C_T + C_B = 1.58$ for dual breaching charges placed on the sloping faces of the top and bottom flanges

Experimental Results: Box Beam AASHO[14]

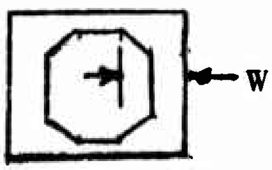
Experimental Charge	No. of Tests	No. of Effective Cuts	Most Effective Charge (lb)	
Pressure				
Tamped	11	10	11.250	(½ charge each side)
Untamped	18	10	22.500	(½ charge each side)
Bottom breaching	24	18	11.8	(½ charge each side)
Shaped Charge	23	17		
M2A3	13	12	23	One 11½ lb/each side
M3	4	3	30	
Linear charge	6	3	> 10	One 5 lb charge on each side

Pressure-tamped formula

$P_{exp} = 11.250$ lb

$H = 30$ in., $H = 900$

$W = 9$ in., maximum flange dimension



$K_{explosive} = 1.34$

$$P_{exp} = \frac{K_{exp} H^2 W}{K_{explosive}}$$

$$11.250 = \frac{K_{exp} \times 900 \times 9}{1.34}$$

$$\boxed{K_{exp} = 0.00787 \text{ lb/in.}^3}$$

Pressure-untamped formula

$P_{exp} = 22.50$ lb.

$$\boxed{K_{exp} = 0.00374 \text{ lb/in.}^3}$$

[14] James A. Dennis, ***Demolition of Prestressed Concrete Box Beams with High-Explosive Charges (Phase III)***, Report 1897, USAERDL, Fort Belvoir, Virginia, April 1967.

Beam Beam (cont'd)

Top-breaching formula

$P = 22.5$ lb (from untamped pressure data)

$R = 30,\ R^3 = 27000$

$K = 0.96$

$K_{explosive} = 1.34$

$$P_{exp} = \frac{5.79 \times 10^{-4}\ R^3 KC}{K_{explosive}}$$

$$22.5 = \frac{5.79 \times 2.7 \times 0.96\ C}{1.34}$$

$$\boxed{\begin{array}{l} C = 2.01 \text{ lb/in.}^3 \\ \text{for dual top breaching charge} \end{array}}$$

Bottom-breaching formula

$P = 11.8$ lb

$R = 30,\ R^3 = 27000$

$K = 0.96$

$K_{explosive} = 1.34$

$$P_{exp} = 5.79 \times 10^{-4}\ R^3\ KC$$

$$11.8 = \frac{5.79 \times 2.7 \times 0.96\ C}{1.34}$$

$$\boxed{\begin{array}{l} C = 1.05 \text{ lb/in.}^3 \\ \text{for dual bottom breaching charge} \end{array}}$$

APPENDIX C

STEEL DATA

1. **Steel Cutting.** Demolition formulae for steel cutting must be applicable to the many basic structural forms as well as many possible fabricated configurations. The following structural shapes could be potential targets for demolition:

Beams	Tees	Plates	Chains
Channels	Angles	Rails	
Tubing	Bars	Piles	
Piping	Rods	Cables	

In addition to the different shapes, there will be steels with various mechanical/structural characteristics with yield stress minimums of 36,000 psi for the carbon steels and 90,000 to 100,000 psi for the quenched and tempered alloy steels.

a. **Formula Parameters.** Steel-cutting formulae capable of application to the wide spectra of steel types and shapes should be based on parameters which are readily identifiable and measurable in the operational environment by military personnel with a minimum of support equipment.

The different structural shapes which require cutting include round, square, rectangular, and irregular cross sections. The characteristic parameters would include diameter for round sections, thickness (or width) for square sections, thickness and widths for rectangular sections, and individual element lengths for irregular sections (approximate methods). Derivations from these parameters would include the respective areas and perimeters for the respective sections. Formulae derived for steel cutting may include as the critical parameter for the target the following:

Structural Element Parameter
D – diameter
D^2 – (diameter)^2
A – Cross section to be cut or fractured

b. **Target Factors Affecting Cutting Relationship.** The material possesses structural properties which determine the energy or work required to cut the element. These factors are the ultimate strengths of the material in shear, tension, and compression. Because the energy required is available from the explosive, it is applied as a shock load and results primarily in shearing action. (The significance of the priming method is summarized in Table C-1.) The primary measure of a material to resist the shock loading is

its toughness. Toughness is a measure of the capacity of a material to absorb large amounts of energy before failure or fracture occurs. Toughness is related to the area under a stress-strain curve and is dependent upon both strength and ductility. Different materials have different toughness characteristics and would reflect in different formulae factors for identical geometric relationship methods of charge application. The element shape determines the element reaction to the explosive energy. Formulae derived for application to steel cutting will contain k_f (form factor) and k_t (toughness factor) plus experimental error as a minimum:

k_t = Average load divided by the cross-sectional area of the member multiplied by the maximum unit strain (in.-lb/in.^{3})

For structural carbon steels at fracture, the maximum unit strain exceeds 0.20. The cross-sectional area to be used in computing k_t should be the contact area of the explosive used or L_E (length of explosive) times W_E (width of explosive).

The average load will vary as a function of the specific element and should vary from 60,000 to 80,000 psi for structural steel which would make

$$k_t = \frac{F x 0.20}{L_E W_E} = 60{,}000\text{–}80{,}000$$

$$\text{or } F = \frac{(60{,}000\text{–}80{,}000)\, L_E W_E}{0.2}$$

$$F = (3\text{–}4) x 10^5\, L_E W_E$$

The work required (W) to shear the steel is the average force F above moving through a distance S (thickness of material T_M) then

$$Fs = FT_M = (3\text{-}4) x 10^5\, L_E W_E x \frac{T_M}{12}$$

$$W = Fs = K.E. \approx 3x10^4\, L_E W_E T_M$$

where

L_E = inches
W_E = inches
T_M = inches
K.E. = Kinetic energy = ft-lb

The fracturing geometry is shown in Fig. C-1.

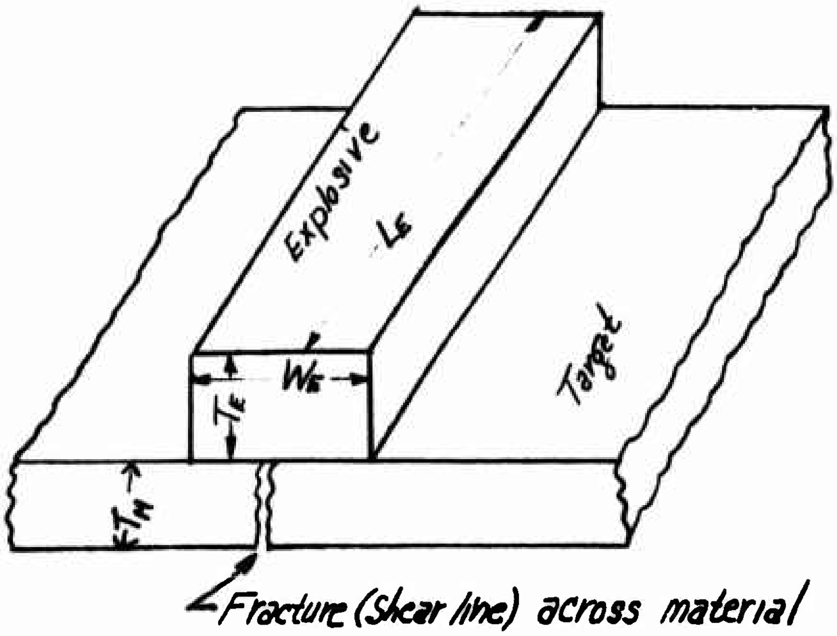


Fig. C-1. Explosive fracturing of steel structural elements.

c. **Energy Available.** The energy required to perform the work of fracturing the element comes from the explosive at detonation:

$$K.E. = \frac{1mV}{2} = \frac{1PV^2}{2g}$$

where m = mass, slugs
P = explosive, lb
g = 32.2 ft/sec²
= acceleration of gravity
V = detonation of velocity, fps

The energy at detonation, unless directed, will be available equally in all directions about the Volume = $W_E L_E T_E$, making only about 1/2 available to act on the contact area $L_E W_E$.

$$\text{Then K.E. available} = \frac{PV^2 K_T}{128.8}$$

where K_T is the energy-transfer coefficient relating the explosive T_E, W_E and material thickness T_M and may be estimated as shown in Fig. C-2.

Discussion of charge placement is contained in Figs. C-3 through C-6.

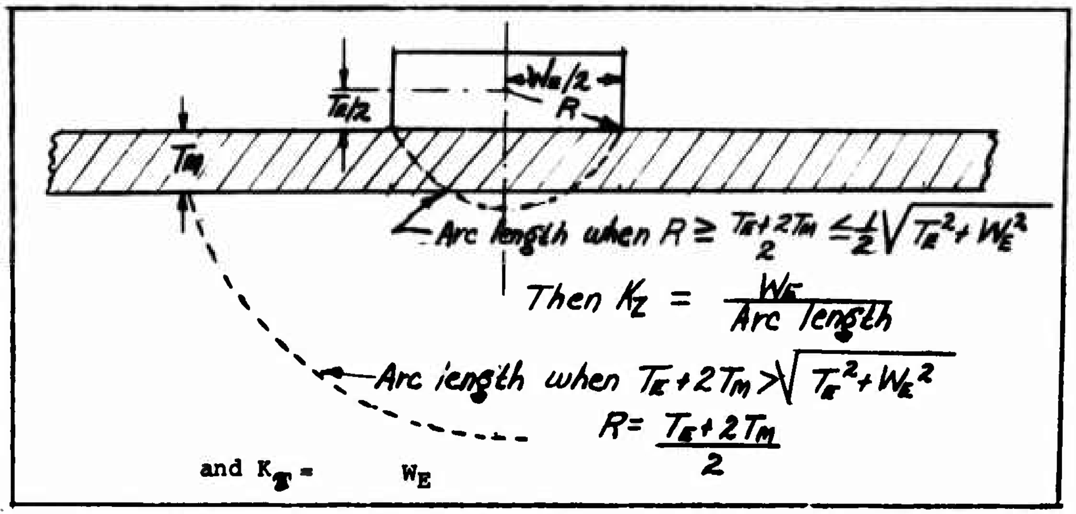


Fig. C-2. Arc length which falls outside the explosive dimensions.

It should be noted that an optimum transfer of energy is possible when T_E and W_E are selected to make $R = \frac{T_E+2T_M}{2}$.

Preliminary calculations for K_T for values of T_E ranging from 0.25 to 2.50 inches inclusive and W_E ranging from 1 to 4 inches inclusive indicate that K_T ranges from $\frac{1}{1.02}$ to $\frac{1}{1.45}$ with the most probable value for T_E = 0.5 and 1.0 and W_E = 3 and 4 inches is K_T $\frac{1}{1.3}$

$$\text{which makes K.E.} = \frac{PV^2}{169} \quad \text{(available)}$$

$K.E. = \frac{PV^2}{169}$ is the energy available at the near face. As the explosive is acting as a line source for wave propagation and the intensity varies as a function of the radius of a cylinder, K.E. available at the far face is 1/2 that at the near face making

$$\text{K.E. (available)} = \frac{PV^2}{338}$$

Explosive	Velocity (V)	V^2	K.E.
TNT	22,600 fps	$5.11 \times 10^8 ft^2/sec^2$	$1.51 \times 10^6 P$
C-4	26,400 fps	$6.97 \times 10^8 ft^2/sec^2$	$2.05 \times 10^6 P$
DS-C	23,600 fps	$5.57 \times 10^8 ft^2/sec^2$	$1.65 \times 10^6 P$

Then K.E. (required) = K.E. (available)

Explosive

TNT $3x10^4 L_E W_E T_M = 1.51x10^6 P$ or $P = 1.99 \times 10^{-2} L_E W_E T_M$

C-4 $3x10^4 L_E W_E T_M = 2.05x10^6 P$ or $P = 1.46x10^{-2} L_E W_E T_M$

DS-C $3x10^4 L_E W_E T_M = 1.65x10^6 P$ or $P = 1.82x10^{-2} L_E W_E T_M$

For W_E = 3-inch and 4-inch

TNT = $P = 5.97x10^{-2} A$: $P = 7.96x10^{-2} A$

C-4 $P = 4.38x10^{-2} A$: $P = 5.84x10^{-2} A$

DS-C $P = 5.46x10^{-2} A$: $P = 7.28x10^{-2} A$

It should be noted that $P = L_E W_E T_E w = kL_E W_E T_M$

where w = unit weight = lb/in.^{3}, then

$$\frac{T_E}{T_M} = \frac{k}{w}$$

Explosive	w	k	T_E/T_M
TNT	$5.63x10^{-2}$ lb/in.^{3}	$1.99x10^{-2}$	1/2.83
C-4	$5.67x10^{-2}$ lb/in.^{3}	$1.46x10^{-2}$	1/3.88
DS-C	$5.35x10^{-2}$ lb/in.^{3}	$1.82x10^{-2}$	1/2.94

2. **Steel Test Data.**

a. **Steel Plate.**

98 Trials : 75 successful cuts

$$P = \frac{0.075A}{K_{explosive}}$$ (Average of all cuts)

Value of constant
P(17% of cuts) = 0.038
P(52% of cuts) = 0.075
P(64% of cuts) = 0.112
P(89% of cuts) = 0.150
P(96% of cuts) = 0.188
P(100% of cuts) = 0.248

A = Cross Section (in.^{2})

P = Explosive (lb)

$K_{explosive}$ = effectiveness factor = k_e

b. **Structural Steel Angle.**

18 Trials : 18 successful cuts

$$P = \frac{0.108A}{K_{explosive}} \quad \text{(Average of all cuts)}$$

Value of constant

P(100% of cuts) = 0.246

P(67% of cuts) = 0.117

P(45% of cuts) = 0.094

c. **Steel Beams.**

106 Trials: 79 successful cuts

$$P = \frac{0.103A}{K_{explosive}} \quad \text{(Average of all cuts)}$$

Value of Constant

P(100% of cuts) = 0.150A

P(66% of cuts) = 0.112A

P(8% of cuts) = 0.008A

d. **Channels.**

15 Trials: 15 successful cuts on one size channel (15x3-3/8)

$$P = \frac{0.074A}{K_{explosive}}$$

Value of Constant

P(min) = 0.070A

P(max) = 0.080A

e. **Wire Ropes.**

Improved Plow Steel

6x19, O.D. = 1.0″; Steel cross section -0.472 in.^{2}, effective d=0.775″

6x7, O.D. = 1.5″; Steel cross section -0.995 in.^{2}, effective d=1.12″

6x19 Tests -9

$$P = \frac{0.73D^2}{K_{explosive}}$$ (for 96-100% of the strands)

where P = lb
D = O.D. inches

Constant Variance
0.59 to 0.73

7x7 Tests -16

$$P = \frac{0.39D^2}{K_{explosive}}$$ (for 94-100% of the strands)

Constant Variance
0.32 to 0.39

6x17, P_{actual} (TNT) $= 0.73D^2$ when D = nominal O.D. = 1.0″

$= 1.21d^2$ when d = effective diameter = 0.775″

$= 0.73D$

$= 0.94d$

7x7 P_{actual} (TNT) $= 0.39D^2$ when D = O.D. = 1.5″

$= 0.70d^2$ when d = effective diameter d = 1.12″

$= 0.59D$

$= 0.79d$

Best correlation when $P \alpha \dfrac{d}{K_{explosive}}$

3. **Cross-Fracture Charge Technique.**

a. **Square Bars.**

43 Trials 24 Successful Cuts

$$P = \frac{0.28A}{K_{explosive}}$$ (Average of all cuts)

Value of Constant
P(100% of cuts) = 0.33
P(92% of cuts) = 0.30
P(50% of cuts) = 0.28
P(37% of cuts) = 0.21

b. **Round Steel Bars.**

40 Trials 13 Successful Cuts

6 Cuts – $P = \frac{0.62D^2}{K_{explosive}}$ (avg)

$P_{max} = \frac{0.93D^2}{K_{explosive}}$

$P_{min} = \frac{0.38D^2}{K_{explosive}}$

(D = 2, 3 inches)

5 cuts – $P = \frac{0.22A}{K_{explosive}}$ (avg)

$P_{max} = \frac{0.33A}{K_{explosive}}$

$P_{min} = \frac{0.12A}{K_{explosive}}$

(D = 4 inches)

4. **Cross-Fracture, Saddle Charges: Round Steel Bars.**

16 Trials 15 Successful Cuts

2″ O.D.

P = 0.41 lb (C-4)

Coefficients for

$P = \frac{\text{Relationship}}{K_{explosive}}$

P	Relationship
0.41	0.27D (2″)
0.41	$0.14D^2$
0.41	0.18A

4 and 6″ O.D.

P = 1.69 lb (C-4) -4″ O.D.
P = 3.68 lb (C-4) -6″ O.D.

Coefficients for

$P = \frac{\text{Relationship}}{K_{explosive}}$

P	Relationship
1.69	0.57D (4″)
1.69	$0.14D^2$
1.69	0.18A
3.68	0.82D (6″)
3.68	$0.14D^2$
3.68	0.17A

Best correlation is obtained with D^2 yielding

$$P = \frac{0.14D^2}{K_{explosive}}$$

5. **Diamond-Shaped Charges.**

a. **Round Steel Rods.**

56 Trials

P	Coefficients Relationship	
.32 lb (avg)	0.215D	(2")
.32	$0.107D^2$	
.32	0.136A	
.59 (avg)	0.264D	(3")
.59	$0.088 D^2$	
.59	0.112A	

39 Successful Cuts

P	Coefficients Relationship	
1.06 lb (avg)	0.355 D	(4")
1.06	$0.089D^2$	
1.06	0.113 A	
1.30 (avg)	0.389 D	(5")
1.30	$0.048D^2$	
1.30	0.061A	

Coefficient Variance (D) 0.215–0.389 = .174/.215 = 81%

(D^2) .107--0.048 = .059/.048 = 123%

(A) .136--0.061 = .075/.061 = 123%

b. **Steel Pipe Charges.**

5 Trials 2 Successful Cuts

One size pipe tested O.D. = 2.375", I.D. = 1.503", A = 2.66 in.^{2}

$$P = 0.505 \text{ lb} = \frac{K_{exp}A}{1.34} \qquad K_{exp} = \frac{0.505 \times 1.34}{2.66} = 0.253$$

6. **Linear-Shaped Charges: Steel Plates.**

DM-19, 19.80 lb of explosive

6 Trials

Crater Volumes

Avg – 227 in.^{3}/charge = 11.5 in.^{3}/lb
Min – 146 in.^{3}/charge = 7.35 in.^{3}/lb
Max – 256 in.^{3}/charge = 12.8 in.^{3}/lb

Improvised, 5.02-7.80 lb of explosive

8 Trials

Crater Volume

Avg – 27.5 in.^{3}/lb
Min – 24.9 in.^{3}/lb
Max – 37.2 in.^{3}/lb

Table C-1. Significance of Priming Methods in Explosive Demolition of Steel Beams

No. of Charges and Their Positions on Steel Beams	Description of Priming Assembly and Points of Initiation of Charges	No. of Test Shots	Complete Cuts	Incomplete Cuts	Primary Cause of Detonation Failure
Three explosive charges that consisted of a continuous charge on half flanges and web on one side of beam, and two half-flange charges on other side, one on each half flange.	Detonating cord priming assembly of three equal lengths of detonating cord with either knots or J-1 caps at one end and J-2 cap that connected other end for simultaneous initiation. Center priming of continuous charge and end priming of half-flange charges.	53	46	7 But none caused by defective priming or initiation.	Insufficient explosive in excessively thin charges in six test shots; low-density C-4 explosive in other test. All charges detonated simultaneously in all 53 test shots.
Two explosive charges continuous over half flanges and web on both sides of beam with charges offset.	Detonating cord priming assembly of two equal lengths of detonating cord with either knots or J-1 caps at one end and J-2 cap that connected other ends for simultaneous initiation. Center priming of both continuous charges.	19	17	2	Lack of simultaneous detonation of two charges apparently caused by non-uniform lengths of detonating cord in priming assemblies or nonuniform rates of detonation in the paste explosive charges (test shots 63 and 65).
Two continuous charges emplaced as described directly above. Charge offset 1 inch.	Two U. S. Army special electric caps in series firing circuit, primed center of two continuous charges.	21	12	9	Excessive charge offset caused one failure; other eight failures resulted from lack of simultaneous detonation caused by variation in times of initiation of two electric blasting caps.
Three charges that consisted of a continuous charge on half flanges and web on one side of beam and two half-flange charges on other side, one on each half flange. Charges offset.	Three U. S. Army special electric caps in series firing circuit, primed center of continuous charge and ends of half-flange charges.	3	1	2	Lack of simultaneous detonation of two charges caused by variations in times of initiation of three electric blasting caps.
Three charges that consisted of a continuous charge on half flanges and web on one side of beam and two half-flange charges on other side, one on each half flange. Charges offset.	Three U. S. Army special electric caps primed ends of two half-flange charges and end of continuous charge.	10	3	7	Excessive charge offset caused one failure; other six failures resulted from lack of simultaneous detonation of two charges produced by variations in times of initiation of three electric blasting caps.

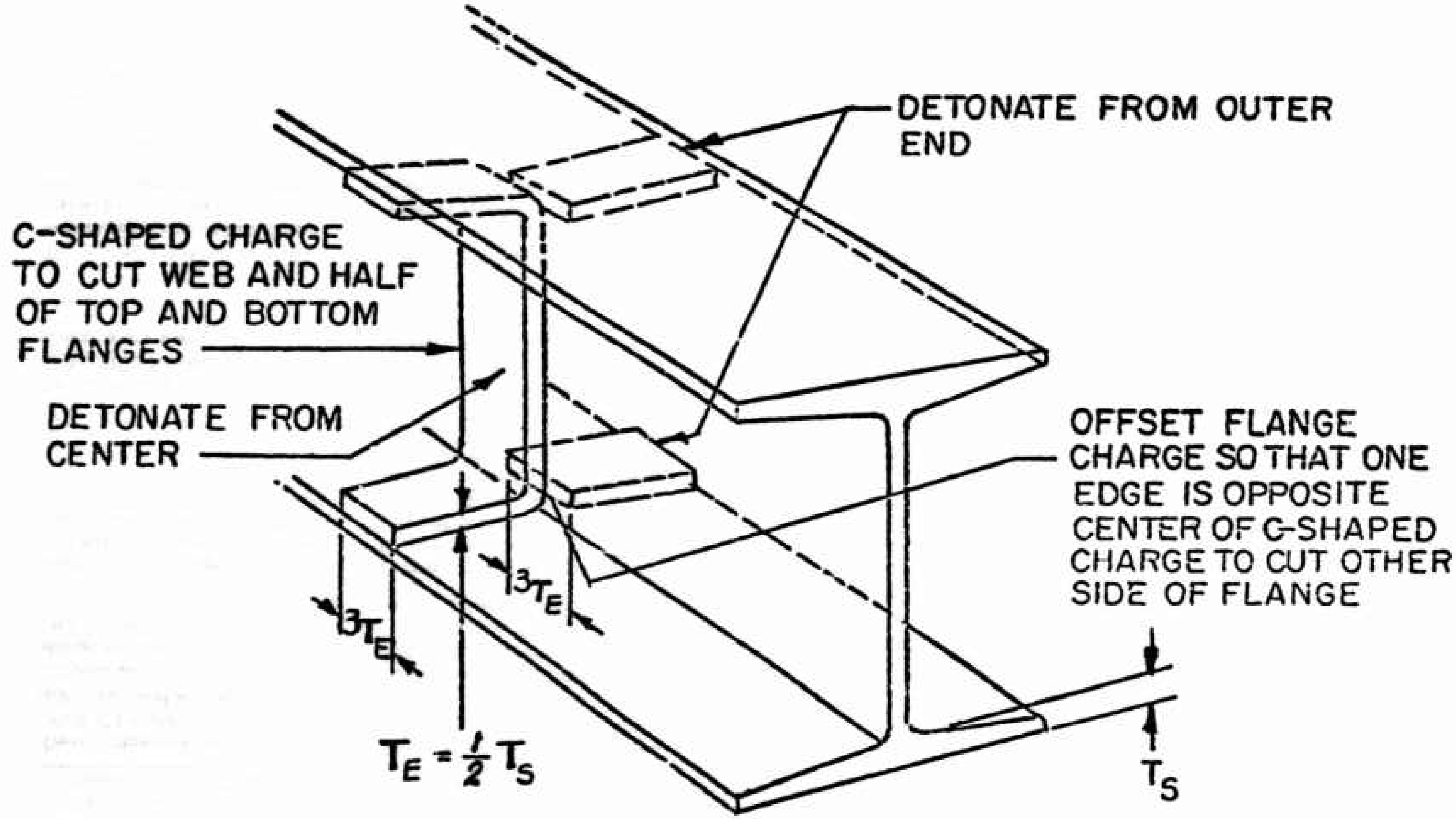


Fig. C-3. Charge placement for explosive cutting of wide-flange beams with steel thicknesses of less than 2 inches.

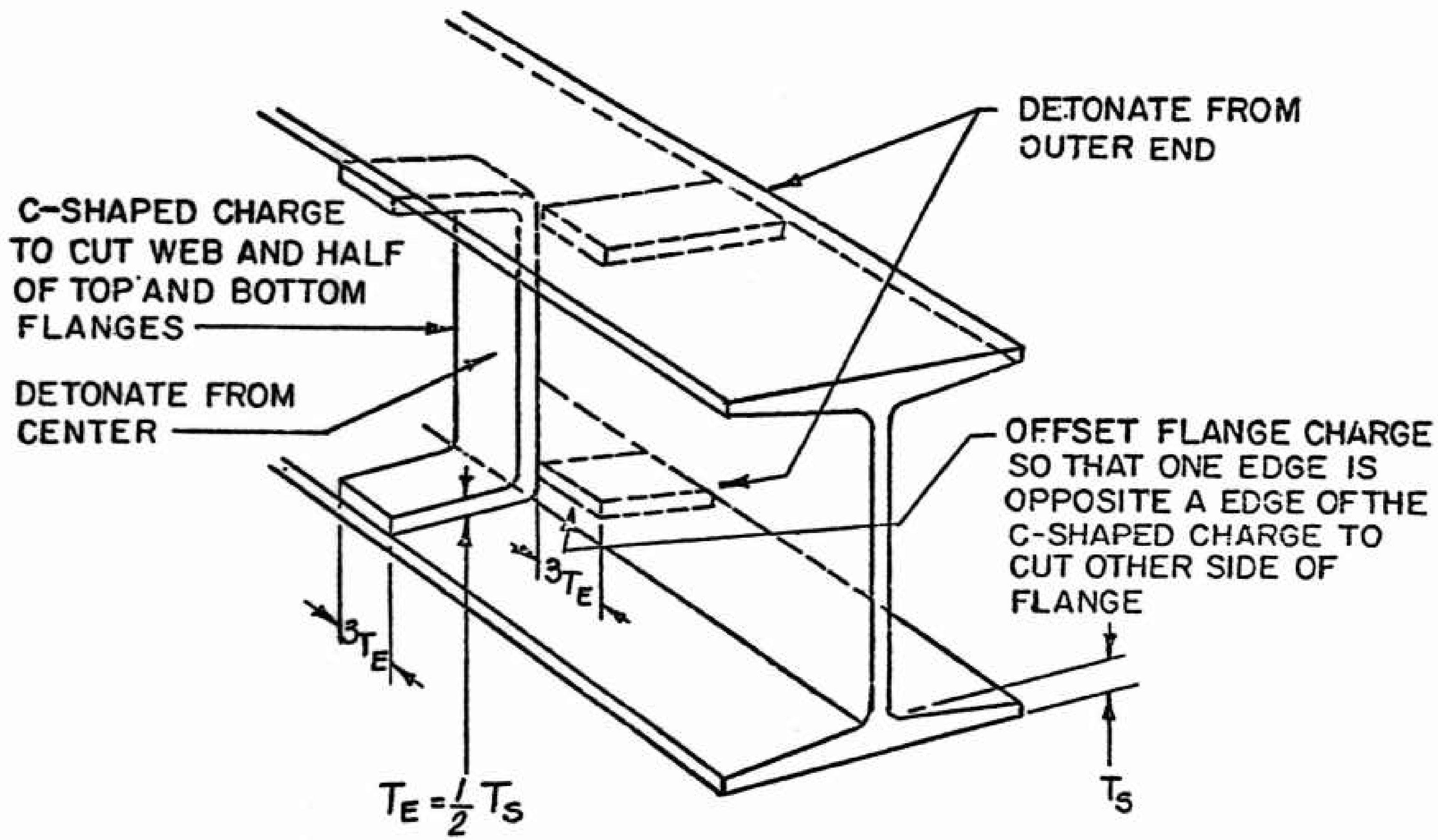


Fig. C-4. Charge placement for explosive cutting of wide-flange beams with steel thicknesses of 2 inches or more.

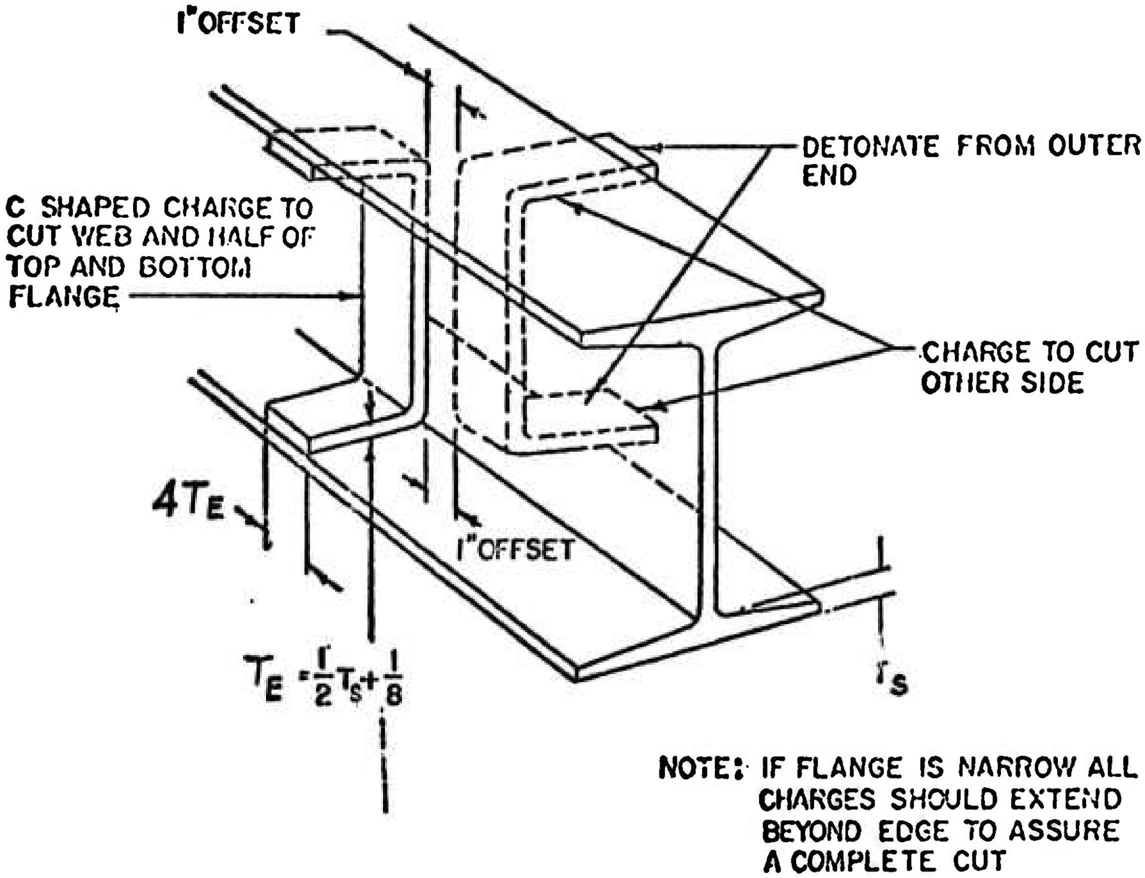


Fig. C-5. U. S. Army charge placement method evaluated for cutting steem beams with explosive charges detonated at center.

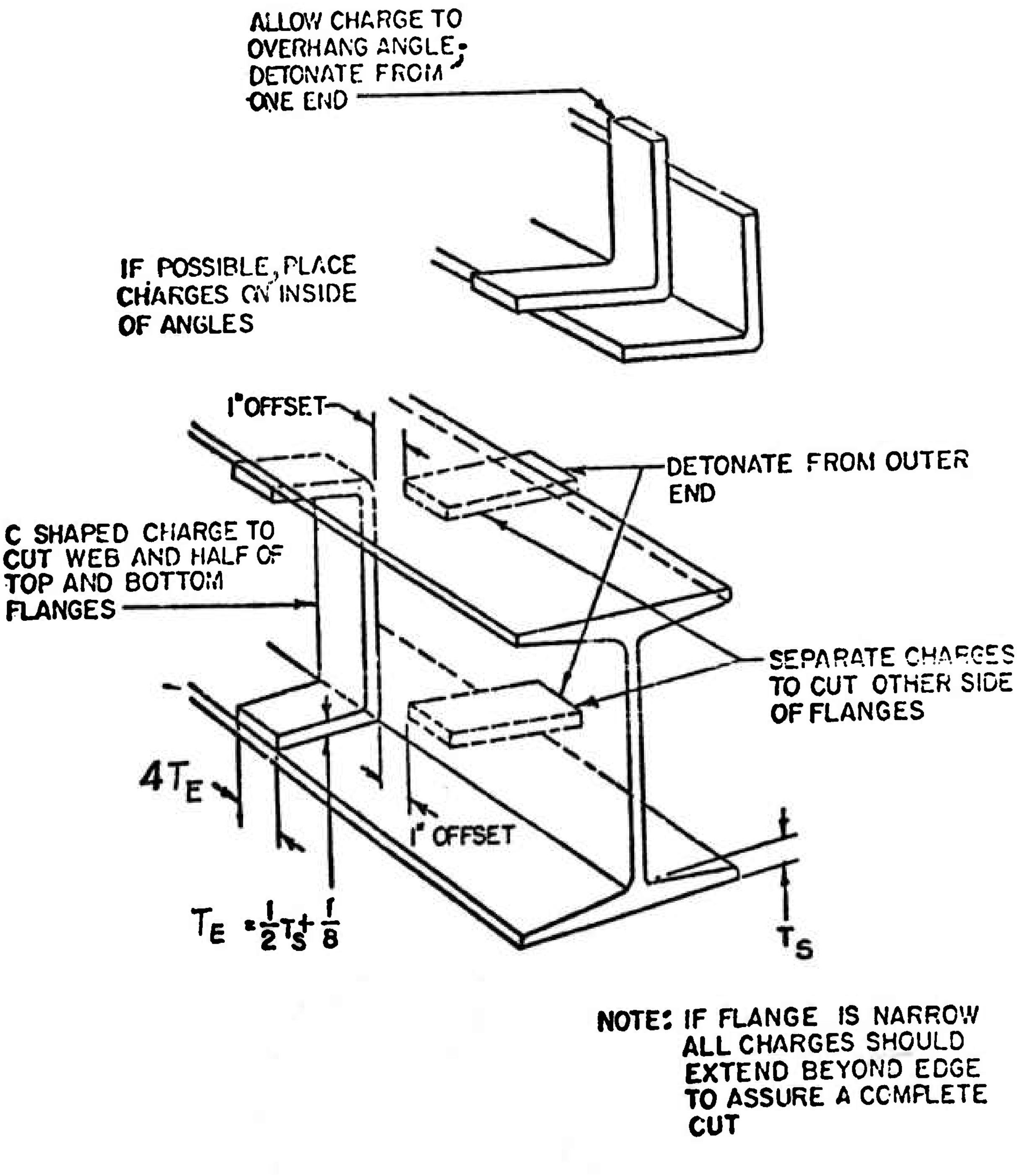


Fig. C-6. Charge placement and priming technique recommended by SRI for explosive cutting of steel beams.

Table D-1. Characteristics of Various Woods

Species	Moisture content (%)	Specific gravity	Static bending					Impact bending—height of drop causing complete failure with 50 lb hammer (in.)	Compression ‖ grain		Compression ⊥ grain—fiber stress at proportional limit (psi)	Shear ‖ grain—maximum shearing strength (psi)	Tension ⊥ to grain—maximum tensile strength (psi)	Hardness: Load required to embed a 0.444-inch ball to 1/2 its diameter	
			Fiber stress at proportional limit (psi)	Modulus of: Rupture (psi)	Modulus of: Elasticity (psi (10^3))	Work to: Proportional limit (in.-lb/in.^{3})	Work to: Maximum load (in.-lb/in.^{3})		Fiber stress at proportional limit (psi)	Maximum crushing strength (psi)				End (lb)	Side (lb)
Fir	38	0.45	4500	7600	1570	0.75	7.6	26	3130	3860	440	930	300	570	500
	12	0.48	7800	12200	1950	1.77	9.8	31	5830	7430	870	1160	340	900	710
Hickory	68	0.59	5300	10000	1380	1.18	10.3	60	3810	4320	980	1260	680	1270	1310
	12	0.65	9100	16300	1780	2.61	18.8	58	5240	8280	2040	2080	--	1930	1820
Red Oak	80	0.56	4400	8500	1360	0.85	12.6	43	2590	3520	800	1220	740	1050	103[illegible]
	12	0.63	8400	14400	1810	2.30	15.0	43	4610	6920	1260	1830	820	1490	1300
White Oak	70	0.59	4700	8100	1200	1.08	11.3	42	2940	3520	850	1270	760	1110	1070
	12	0.67	7900	13900	1620	2.31	13.3	39	4350	7040	1410	1890	770	1420	1330
Sweet gum	81	0.44	3700	6800	1150	0.81	9.4	33	2230	2840	460	1070	510	630	520
	12	0.49	8100	11900	1490	2.57	11.3	32	4700	5800	860	1610	800	950	690

APPENDIX D

TIMBER DATA

1. **General.** Table 1 shows the general formulae used for tamped and untamped charges used for timber cutting. Table 2 shows these formulae when calculating charges for TNT, Composition C-4, and Detasheet C. It must be pointed out that the demolition requirements and constraints shown in Fig. 1 apply to the cutting of timber by explosive charges.

Further, there are differences between the different species of trees as well as physical and structural variations within each species. Table D-1 shows the average characteristics which apply to the five species of trees which were considered for the experimental program in ERDL Report 1900.[15] Again, it should be pointed out that there would be variance within each species. The higher value of moisture content for each species in Table D-1 denotes the "green" condition while the lower value denotes the structural lumber condition.

Noting the values for the "green" condition in the Impact Bending Column of Table D-1, the following is indicated for the various species: The height of impact causing complete failure with a 50-lb hammer and the relative kinetic energy requirements are shown in Table D-2.

Table D-2. Timber Cutting—Species/Kinetic Energy Relationships

Species	Height of Fall (in.)	Relative Kinetic Energy Requirements				
Hickory	60	2.3	1.8	1.4	1.4	1.0
Red Oak	43	1.6	1.3	1.0	1.0	0.7
White Oak	42	1.6	1.3	1.0	1.0	0.7
Sweet Gum	33	1.3	1.0	0.8	0.8	0.6
Fir	26	1.0	0.8	0.6	0.6	0.4

The values in Table D-2 show the results of testing at the Timber Products Laboratory and are obtained from NAVSHIPS 250-336.

[15] James A. Dennis, *Comparison of Composition C-4 Explosive and M118 Demolition Charges (Detasheet C Explosive) for Military Demolitions*, Report 1900, USAERDL, Fort Belvoir, Virginia, June 1967.

It must be pointed out that the results shown were gained from laboratory test specimens and when applied to trees still in a growth configuration may not reflect the numerical relationship shown in Table D-2, but the order of energy relationship (least... most) should remain significant.

Other factors affecting demolition effectiveness of timber relate to the explosive, its placement, and its initiation; the tree, the thickness of the bark, the lack of growth symmetry, physical and structural characteristics; the military environment and requirements; and supporting equipment.

2. **Experimental Data.** Table D-3 shows the timber-cutting data points which were obtained in the experimental program in ERDL Report 1900.[16]

Table D-3. Experimental Test Program Resultants

Resultant of Timber-Cutting Tests	Explosive Used (Number of Charges)		
	Comp. C-4	Detasheet C	TNT
Number of charges	8	14	3
Number cut and felled	6	5	2
Number cut and not felled	0	6	0
Marginal fall	2	3	1

Table D-4 shows the timber-cutting charge calculations for diameters from 1 inch to 40 inches in 1-inch increments for TNT, Composition C-4, and Detasheet-C. Table D-4 contains the associated circumference for each diameter. It should be pointed out that the circumference may be more easily obtainable in the field or operational environment than would the estimate of the diameter of the tree, making the following formulae more applicable for development of explosive tables for timber-cutting calculations:

$$\left.\begin{array}{ll}\text{External} & P = 0.00253\ c^2 \\ \text{Internal} & P = 0.000405\ c^2\end{array}\right\}\ \text{TNT}$$

$$\left.\begin{array}{ll}\text{External} & P = 0.00222\ c^2 \\ \text{Internal} & P = 0.000356\ c^2\end{array}\right\}\ \text{Detasheet-C}$$

$$\left.\begin{array}{ll}\text{External} & P = 0.00190\ c^2 \\ \text{Internal} & P = 0.000304\ c^2\end{array}\right\}\ \text{Composition C-4}$$

(c = Circumference of tree trunk in inches at point of application of explosive charge.)

[16] James A. Dennis, *Comparison of Composition C-4 Explosive and M118 Demolition Charges (Detasheet C Explosive) for Military Demolitions*, Report 1900, USAERDL, Fort Belvoir, Virginia, June 1967.

Table D-4. Timber-Cutting Charge Calculations

D (in.)	D^2 $(in.)^2$	TNT $P=0.025\ D^2$ (lb)	Composition C-4 $P=0.0187\ D^2$ (lb)	Detasheet-C $P=0.0219\ D^2$ (lb)	Circumference (in.)
1	1	0.0250	0.0187	0.0219	3.2
2	4	0.100	0.0748	0.0876	6.3
3	9	0.226	0.168	0.197	9.5
4	16	0.400	0.299	0.350	12.6
5	25	0.625	0.468	0.547	15.7
6	36	0.900	0.673	0.789	18.9
7	49	1.22	0.917	1.07	22.0
8	64	1.60	1.19	1.40	25.2
9	81	2.03	1.51	1.77	28.3
10	100	2.50	1.87	2.19	31.5
11	121	3.02	2.26	2.65	34.6
12	144	3.60	2.70	3.16	37.7
13	169	4.23	3.16	3.70	40.9
14	196	4.90	3.67	4.30	44.0
15	225	5.63	4.21	4.93	47.2
16	256	6.40	4.78	5.62	50.3
17	289	7.23	5.40	6.33	53.4
18	324	8.10	6.06	7.11	56.6
19	361	9.03	6.75	7.92	59.7
20	400	10.00	7.48	8.76	62.9
21	441	11.03	8.25	9.67	66.0
22	484	12.10	9.01	10.6	69.2
23	529	13.2	9.88	11.6	72.3
24	576	14.4	10.8	12.6	75.4
25	625	15.6	11.7	13.7	78.6
26	676	16.9	12.6	14.8	81.7
27	729	18.2	13.6	16.0	84.9
28	784	19.6	14.7	17.1	88.0
29	841	21.0	15.7	18.4	91.1
30	900	22.5	16.8	19.7	94.3
31	961	24.0	18.0	21.1	97.4
32	1024	25.6	19.2	22.5	100.6
33	1089	27.3	20.4	23.9	103.7
34	1156	28.9	21.6	25.3	106.8
35	1225	30.6	22.9	26.8	110.0
36	1296	32.4	24.2	28.4	113.1
37	1369	34.2	25.6	30.0	116.3
38	1444	36.1	27.0	31.6	119.4
39	1521	38.0	28.4	33.3	122.6
40	1600	40.0	29.9	35.1	125.7

Table D-5 shows the timber-cutting charge calculations and the experimental data realized for five species of trees, diameters from 12.5 to 27.0 inches, and for Composition C-4, Detasheet-C, and TNT. It should be noted that in only three cases were the calculated charges less than the actual data realized by experimentation. It is unfortunate that more test data were not realized for TNT (3 data points only).

Table D-6 contains the experimental data for only the complete or marginal-complete test shots for the timber-cutting experiments. The purpose of the table was to derive a new constant for the external-charge, timber-cutting formula based on the assumption that the deviations appearing in the test data are random and that the targets/test conditions/techniques approximate normal field applications. The following were derived:

Coefficient	C-4	DS-C	TNT
Mean Value	0.0139	0.0179	0.0289
89% of Cases	0.0157	0.0214	0.0310
98% of Cases	0.0175	0.0249	0.0331
99.8% of Cases	0.0193	0.0284	0.0352

Table D-5. Timber Cutting (Calculations/Experimental Data)

Timber Species	Diameter (in.)	Explosive Charge Data: C-4 Calc. (lb)	C-4 Act. (lb)	C-4 Calc./Act. (%)	Detasheet-C Calc. (lb)	Detasheet-C Act. (lb)	Detasheet-C Calc./Act. (%)	TNT Calc. (lb)	TNT Act. (lb)	TNT Calc./Act. (%)	Resultant
Hickory	18.0				7.11	7.00	102				M
Red Oak	12.5	2.92	1.94	151							C
	15.0				4.93	3.50	141				C
	15.0				4.93	4.00	123				C
	15.3				5.12	2.00	256				I
	16.0	4.78	3.37	142							C
	16.0				5.62	4.00	140				C
	17.5							7.67	8.00	96	M
	18.0	6.06	5.25	164							C
	19.0				7.92	5.00	158				I
	22.1				10.67	6.00	177				I
	22.4							12.53	13.50	93	C
	24.3				12.90	12.94	100				C
	27.0	13.6	9.75	139							M
Red Oak	27.0				16.0	10.00	160				I
White Oak	12.7	3.02	2.00	151							C
	15.0				4.93	3.50	141				I
	15.2	4.33	2.75	158							C
	16.6							6.88	8.50	81	C
	19.0	6.75	5.25	128							C
	19.0				7.92	7.00	113				M
White Oak	21.0				9.67	7.00	138				I
Sweet Gum	17.0	5.40	5.00	108							M
Sweet Gum	18.5				7.51	7.00	107				M
Fir	11 □(square cross-section)				2.65	1.32	201				C

M = marginal; C = complete cut; I = incomplete cut

Table D-6. Experimental Coefficients (Timber Cutting Formula)

Composition C-4						Detasheet-C						TNT					
Diameter–D (in.)	(Diameter)^2–D^2(in.)^2	Experimental Charge–P (lb)	$P/D^2 = k$ (lb/in.^{2})	$k - \bar{k}$ (lb/in.^{2})	$(k - \bar{k})^2$ (lb/in.^{2})^2	Diameter–D (in.)	(Diameter)^2–D^2 (in.)^2	Experimental Charge–P (lb)	$P/D^2 = k$ (lb/in.^{2})	$k - \bar{k}$ (lb/in.^{2})	$(k - \bar{k})^2$ (lb/in.^{2})^2	Diameter–D (in.)	(Diameter)^2–D^2 (in.)^2	Experimental Charge–P (lb)	$P/D^2 = k$ (lb/in.^{2})	$k - \bar{k}$ (lb/in.^{2})	$(k - \bar{k})^2$ (lb/in.^{2})^2
12.5	156	1.94	0.0124	-0.0015	225×10^{-8}	18.0	324	7.00	0.0216	+0.0037	1369×10^{-8}	17.5	306	8.00	0.0261	-0.0028	784×10^{-8}
16.0	256	3.37	0.0132	-0.0007	49	15.0	225	3.50	0.0155	-0.0024	576	22.4	502	13.50	0.0298	+0.0009	81
18.0	324	5.25	0.0163	+0.0024	576	15.0	225	4.00	0.0178	-0.0001	1	16.6	276	8.50	0.0309	+0.0020	400
27.0	729	9.75	0.0134	-0.0003	25	16.0	256	4.00	0.0157	-0.0022	484						
12.7	161	2.00	0.0124	-0.0015	225	24.3	590	12.94	0.0219	+0.0040	1600						
15.2	231	2.75	0.0119	-0.0020	400	19.0	361	7.00	0.0194	+0.0015	225						
19.0	361	5.25	0.0145	+0.0006	36	18.3	342	7.00	0.0205	+0.0026	676						
17.0	289	5.00	0.0173	+0.0034	1156	11.0	121	1.32	0.0109	-0.0070	4900						
Σ	2537	35.31	0.1114	+0.0002	2692×10^{-8}	Σ	2444	46.76	0.1433	+0.0001	9831×10^{-8}	Σ	1084	30.00	0.0868	+0.0001	1265×10^{-8}
Mean	317	4.41	0.0139	+0.00003	336×10^{-8}	Mean	306	5.84	0.0179	+0.00001	1229×10^{-8}	Mean	361	10.00	0.0289	+0.00001	422×10^{-8}
RMS				±0.0018		RMS				±0.0035		RMS				±0.0021	

APPENDIX E

MATHEMATICAL TABLES

1. **General.** This appendix contains tables which were developed to facilitate calculations of the formulae which require the square or the cube of numbers which reflect the parameters of the height (H), the radius (R), or the diameter (D) of a demolition target.

Table E-1 contains the squares and cubes of numbers from 1 to 140 and should prove useful for the formulae shown in Tables 1 and 2 and the timber-cutting formulae involving the circumference in Appendix D.

Table E-2 should have application to the calculation of breaching charges when (R) is in feet and tenths of feet for a range of (R) from 0.0 through 10.9.

The data contained in Tables E-1 and E-2 can be used to establish specific tables for each explosive and each target formula. An example is shown in Table E-4 for D in increments of 1 inch for TNT, Detasheet-C, and Composition C-4 when employed for timber-cutting calculations from D=1 to D=40 inches. In using such tables, the demolition personnel have only to determine the field measurement of the parameter and use this parameter value to enter the table for the appropriate explosive. The value in the table is the required weight of the explosive in pounds.

2. **Significance of Measurements.** It should be noted from Table E-1 that the significance of an error of 1 inch varies as follows for the following parametric values:

N	N	N^2	N^3
3	(+33, -33) %	(+78, -56) %	(+137, -71) %
10	(+10, -10)	(+21, -19)	(33, -27)
20	(+5, -5)	(+10.2, -9.7)	(+15.8, -14.3)
40	(+2.5, -2.5)	(+5.1, -5.0)	(+7.7, -7.3)
100	(+1.0, -1.0)	( )	

3. **Recommended Table Development.** The formulae as presented in FM 5-25 should be expanded into tables, or a slide rule should be developed to minimize the number of mathematical calculations required. Ideally, the user should enter the tables with a single measurement and determine the proper number of explosive packages, blocks, or sheets which are required to demolish the target—no calculations should be necessary. Tables E-1 thru E-6 in this appendix are included to facilitate required calculations.

4. **Explosive Charge Tolerances.** The following explosive increments or packages are from Table A-2, Appendix A, which contains data about standard blocks of military explosives:

0.0417 lb	based upon an assumed operation capability of ± 1-inch tolerance in cutting the 1/4 x 3 x 12 (1/2-lb) sheet of the M118 block or the M186 roll.
0.25 lb	based upon the smallest TNT package.
0.50 lb	based upon the TNT package and the M118, 1/4 x 3 x 12 sheet.
1.00 lb	based upon the TNT package.
1.25 lb	based upon the M112 block.
2.00 lb	based upon the M118 block.
2.50 lb	based upon the M5A1 block.

Any tables or slide rules developed should yield an answer to the respective standard package increment or tolerance as applicable to minimize any possible error through field calculation of the number of standard packages which constitute the required demolition charge.

Table E-1. Mathematical Tables (Squares/Cubes)

N	N^2	N^3	N	N^2	N^3
1	1	1	39	1521	59319
2	4	8	40	1600	64000
3	9	27	41	1681	68921
4	16	64	42	1764	74088
5	25	125	43	1849	79507
6	36	216	44	1936	85184
7	49	343	45	2025	91125
8	64	512	46	2116	97336
9	81	729	47	2209	103823
10	100	1000	48	2304	110592
11	121	1331	49	2401	117649
12	144	1728	50	2500	125000
13	169	2197	51	2601	132651
14	196	2744	52	2704	140608
15	225	3375	53	2809	148877
16	256	4096	54	2916	157464
17	289	4913	55	3025	166375
18	324	5832	56	3136	175616
19	361	6859	57	3249	185193
20	400	8000	58	3364	195112
21	441	9261	59	3481	205379
22	484	10648	60	3600	216000
23	529	12167	61	3721	226981
24	576	13824	62	3844	238328
25	625	15625	63	3969	250047
26	676	17576	64	4096	262144
27	729	19683	65	4225	274625
28	784	21952	66	4356	287496
29	841	24389	67	4489	300763
30	900	27000	68	4624	314432
31	961	29791	69	4761	328509
32	1024	32768	70	4900	343000
33	1089	35937	71	5041	357911
34	1156	39304	72	5184	373248
35	1225	42875	73	5329	389017
36	1296	46656	74	5476	405224
37	1369	50653	75	5625	421875
38	1444	54872	76	5776	438976

Table E-1 (cont'd)

N	N^2	N^3	N	N^2	N^3
77	5929	456533	94	8836	830584
78	6084	474552	95	9025	857375
79	6241	493039	96	9216	884736
80	6400	512000	97	9409	912673
81	6561	531441	98	9604	941192
82	6724	551368	99	9801	970299
83	6889	571787	100	10000	1000000
84	7056	592704	101	10201	1030301
85	7225	614125	102	10404	1061208
86	7396	636056	103	10609	1092727
87	7569	658503	104	10816	1124864
88	7744	681472	105	11025	1157625
89	7921	704969	106	11236	1191016
90	8100	729000	107	11449	1225043
91	8281	753571	108	11664	1259712
92	8464	778688	109	11881	1295029
93	8649	804357	110	12100	1331000

Table E-2. Mathematical Tables (Number/Cubes)

R	R^3									
	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0.0	0	0.0010	0.0040	0.0270	0.0640	0.1250	0.2160	0.3430	0.5120	0.7290
1.0	1.000	1.331	1.728	2.197	2.744	3.375	4.096	4.913	5.832	6.859
2.0	8.0000	9.261	10.648	12.167	13.824	15.625	17.576	19.683	21.952	24.389
3.0	27.000	29.791	32.768	35.937	39.304	42.875	46.656	50.653	54.872	59.319
4.0	64.000	68.921	74.088	79.507	85.184	91.125	97.336	103.82	110.59	117.65
5.0	125.00	132.65	140.61	148.88	157.46	166.375	175.62	185.19	195.11	205.38
6.0	216.00	226.98	238.33	250.05	262.14	274.625	287.50	300.76	314.43	328.51
7.0	343.00	357.91	373.25	389.02	405.22	421.875	438.98	456.53	474.55	493.04
8.0	512.00	531.44	551.37	571.79	592.70	614.13	636.06	658.50	681.47	704.97
9.0	729.00	753.57	778.69	804.36	830.58	857.38	884.74	912.67	941.19	970.30
10.0	1000.0	1030.3	1061.2	1092.7	1124.9	1157.6	1191.0	1225.0	1259.7	1295.0

Table E-3. KC Products (Breaching Formula)

Value for (C) Tamping Factor (Fig. 3-13 FM 5-25)	Material Factor (K) (Table 3-2 FM 5-25)																
	0.07	0.27	0.29	0.32	0.35	0.40	0.41	0.48	0.52	0.54	0.62	0.63	0.80	0.88	0.96	1.14	1.76
1.0	0.07	0.27	0.29	0.32	0.35	0.40	0.41	0.48	0.52	0.54	0.62	0.63	0.80	0.88	0.96	1.14	1.76
1.2	0.08	0.32	0.35	0.38	0.42	0.48	0.49	0.58	0.62	0.65	0.74	0.76	0.96	1.06	1.15	1.37	2.11
1.4	0.10	0.38	0.41	0.45	0.49	0.56	0.57	0.67	0.73	0.76	0.87	0.88	1.12	1.23	1.34	1.60	2.46
1.6	0.11	0.43	0.46	0.51	0.56	0.64	0.66	0.77	0.83	0.86	0.99	1.01	1.28	1.41	1.54	1.82	2.82
1.8	0.13	0.49	0.52	0.58	0.63	0.72	0.74	0.86	0.94	0.97	1.12	1.13	1.44	1.58	1.73	2.05	3.17
2.0	0.14	0.54	0.58	0.64	0.70	0.80	0.82	0.96	1.04	1.08	1.24	1.26	1.60	1.76	1.92	2.28	3.52
2.2	0.15	0.59	0.64	0.70	0.77	0.88	0.90	1.06	1.14	1.19	1.36	1.39	1.76	1.94	2.11	2.51	3.87
2.4	0.17	0.65	0.70	0.77	0.84	0.96	0.98	1.15	1.25	1.30	1.49	1.51	1.92	2.11	2.30	2.74	4.22
2.6	0.18	0.70	0.75	0.83	0.91	1.04	1.07	1.25	1.36	1.40	1.61	1.64	2.08	2.29	2.50	2.96	4.58
2.8	0.20	0.76	0.81	0.90	0.98	1.12	1.15	1.34	1.46	1.51	1.74	1.76	2.24	2.46	2.69	3.19	4.93
3.0	0.21	0.81	0.87	0.96	1.05	1.20	1.23	1.44	1.56	1.62	1.86	1.89	2.40	2.64	2.88	3.42	5.28
3.2	0.22	0.86	0.93	1.02	1.12	1.28	1.31	1.54	1.67	1.73	1.98	2.02	2.56	2.82	3.07	3.65	5.63
3.4	0.24	0.92	0.99	1.09	1.19	1.36	1.39	1.63	1.78	1.84	2.11	2.14	2.72	2.99	3.26	3.88	5.98
3.6	0.25	0.97	1.04	1.15	1.26	1.44	1.48	1.73	1.88	1.94	2.23	2.27	2.88	3.17	3.46	4.10	6.34

Table E-4. Explosive Weights, Thickness Versus Length (Width = 3 charge thickness)

Thickness	Weight of Explosive (lb) When Width = 3 Charge Thickness												
	Length of Charge in Inches												
(in.)	1	2	3	4	5	6	7	8	9	10	11	12	13
0.250	.0424	.0848	.1271	.1695	.2119	.2542	.2966	.3390	.3814	.4238	.4661	.5085	.5509
0.500	.0848	.1695	.2542	.3390	.4238	.5085	.5932	.6780	.7628	.8475	.9322	1.0170	1.1018
0.750	.1271	.2542	.3814	.5085	.6356	.7628	.8898	1.0170	1.1441	1.2712	1.3984	1.5255	1.6526
1.000	.1695	.3390	.5085	.6780	.8475	1.0170	1.1865	1.3560	1.5255	1.695	1.8645	2.0340	2.2035
1.250	.2119	.4238	.6356	.8475	1.0594	1.2712	1.4831	1.6950	1.9069	2.1188	2.3306	2.5425	2.7544
1.500	.2542	.5085	.7628	1.0170	1.2712	1.5255	1.7798	2.0340	2.2882	2.5425	2.7968	3.0510	3.3052
1.750	.2966	.5933	.8899	1.1865	1.4831	1.7798	2.0764	2.3730	2.6696	2.9662	3.2629	3.5595	3.8561
2.000	.3390	.6780	1.0170	1.3560	1.6950	2.0340	2.3730	2.7120	3.0510	3.390	3.7290	4.068	4.4070

Applicable for C-4 and TNT

Table E-5. Explosive Weights, Thickness Versus Length (Width = 4 charge thickness)

Thickness	Weight of Explosives (lb) When Width = 4 Charge Thickness												
	Length of Charge in Inches												
(in.)	1	2	3	4	5	6	7	8	9	10	11	12	13
0.250	.0565	.1130	.1695	.2260	.2825	.3390	.3955	.4520	.5085	.565	.6215	.678	.7345
0.500	.1130	.2260	.3390	.452	.5650	.6780	.7910	.9040	1.0170	1.130	1.2430	1.356	1.4690
0.750	.1695	.3390	.5085	.678	.8475	1.0170	1.1865	1.3560	1.5255	1.695	1.8645	2.034	2.2035
1.000	.2260	.4520	.6780	.904	1.1300	1.3560	1.5820	1.8080	2.0340	2.260	2.4860	2.712	2.938
1.250	.2825	.5650	.8475	1.130	1.4125	1.6950	1.9775	2.2600	2.5425	2.825	3.1075	3.390	3.6725
1.500	.3390	.6780	1.1170	1.356	1.6950	2.034	2.3730	2.7120	3.0510	3.390	3.729	4.068	4.407
1.750	.3955	.7910	1.186	1.582	1.9775	2.373	2.7685	3.1640	3.5595	3.955	4.3505	4.746	5.1415
2.000	.4520	.9040	1.356	1.808	2.2600	2.712	3.1640	3.6160	4.0680	4.520	4.9720	5.424	5.8760

Applicable for C-4 and TNT

Table E-6. Structural Steel Cutting Formula Constants

	Value for K									
W_E (in.)	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9
0		.0019	.0038	.0058	.0077	.0096	.0115	.0134	.0154	.0173
1	.0192	.0211	.0230	.0250	.0269	.0288	.0307	.0326	.0346	.0365
2	.0384	.0403	.0422	.0442	.0461	.0480	.0499	.0518	.0538	.0557
3	.0576	.0595	.0614	.0634	.0653	.0672	.0691	.0710	.0730	.0749
4	.0768	.0787	.0806	.0826	.0845	.0864	.0883	.0902	.0922	.0941
5	.0960	.0979	.0998	.1018	.1037	.1056	.1075	.1094	.1114	.1133
6	.1152	.1171	.1190	.1210	.1229	.1248	.1267	.1286	.1306	.1325
7	.1344	.1363	.1382	1402	.1421	.1440	.1459	.1478	.1498	.1517
8	.1536	.1555	.1574	.1594	.1613	.1632	.1651	.1670	.1690	.1709
9	.1728	.1747	.1766	.1786	.1805	.1824	.1843	.1862	.1882	.1901
10	.192	.1939	.1958	.1978	.1997	.2016	.2035	.2054	.2074	.2093

$$P = 1.92 \times 10^{-2} \frac{L_E W_E T_M}{K_{explosive}} = 1.92 \times 10^{-2} W_E \frac{A}{K_{explosive}} = K \frac{A}{K_{explosive}}$$

$K_{explosive}$

TNT = 1.00
C-4 = 1.34
DS-C = 1.14